

Effects of Air Movement, Inversions and Other
External Heat Sources on Plant and Air
Temperatures in Relation to Cold
and Frost Injury of Plants

By
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I. INTRODUCTION

Production and marketing of horticultural crops are major sources of Florida's income from agriculture. Most of these crops are subject to frost or freeze damage. The financial risks are high and growers have long sought economical ways to reduce this risk.

Early frost protection measures in Florida included coke heaters, coal baskets, oil heaters, and wood fires. Garriott (27) commented on a grower who protected an extensive grove by building a wooden shed over it and burned small wood fires underneath the shed for added protection. The wooden top was removed after the danger of frost was past. One of the most unique bits of history even reports on an arrangement between the Weather Bureau and the railroads to give freezing forecasts with whistle signals to growers along the line. Camp (19, 20) and other early research workers made observations on cold protection by growers but reported very little actual research on frost protection. These early studies indicated that heating with wood fires was the most economical protection available to growers where "fat pine" wood was readily available as fuel. The first definite effort to reduce risks from cold came with organization of the Federal-State Horticultural Protection Service in 1935 (25). They began by giving citrus growers forecasts of

minimum temperatures in the fall of 1935 and later expanded their work to include studies on frost protection methods practical for all horticultural crops (46).

A review of Weather Bureau records indicated that frost can be a hazard in fruit and vegetable growing areas of Florida every season. Severe freezes occur much less frequently. There are detailed reports in the literature on the severe freezes of 1894-95 and in 1899. Webber (50) writes of the freezes that occurred December 27, 28, and 29, 1894, and February 7, 8, and 9, 1895. The freeze in 1894 was accompanied by winds of 25-30 mph and temperatures dropped to 14°F at Jacksonville and 16-19°F throughout central Florida. It is generally believed difficult for most growers to provide more than partial protection for these most severe freezes.

The present research project was initiated to seek additional information and determine possible ways to reduce risk from frost and provide partial protection from infrequent severe freezes. The wind machine was tested as a device for mechanically mixing overhead air with air near the ground. The effects of the mixing on ambient air temperatures and the relative effects on tissue temperatures were measured. Results indicated that the wind machine provided some protection on cold, clear, calm nights.

II. REVIEW OF LITERATURE

Protection against frost and freezing has been a goal sought by horticulturists and husbandmen for as long as there has been production of horticultural crops. Frost was early recognized as one of the most formidable foes of the fruit grower in the United States. Since much has been written on the subject, no attempt was made to give a complete review of the literature available on frost and freezing. Some historical literature pertinent to the research to be reported was selected and a fairly complete and up-to-date review of literature on the mechanical mixing of stratified air as a means of frost protection was made.

Perhaps some of the first people to attempt to prevent frost formation were the husbandmen of vineyards in Europe. They observed that frosts seldom came on cloudy nights and tried to create clouds on clear nights by burning wet straw and manures. When practiced in a large area by a number of small vineyards, the procedure was generally beneficial. Brackett (7) reports on an Austrian who used explosives strategically placed around a valley to "drive" away frosts and hail. The gun powder was fired simultaneously around the area and continued at intervals as long as the threat existed. The claimed success was later attributed to the mechanical mixing of stratified air by the explosives.

Regular meteorological observations and forecasting began in the second half of the 19th century. Some scientists in Germany soon

began to notice that the broad area data collected did not always apply to the needs of agriculture. Some of them began to study the air layer adjacent to the ground and the forces that affected plants. Much of this work was summarized by Rudolph Geiger (28, 29). Geiger coined the word micro-climate and took the definition of G. Kraus, "climate in the least space." He also named microclimatology as the science of micro-climate.

Meteorological investigations in this country began as a function of the Signal Service. Non-governmental work in the field was being done by a few scientists connected with observatories and colleges. Of significant interest to agriculture was the transfer of meteorologists in the Signal Service to the United States Department of Agriculture and the creation of the Weather Bureau in the U.S.D.A. in 1891. Harrington (35), Chief of the Weather Bureau, almost immediately started calling farmers' attention to what meteorology could do for agriculture.

Fruit growers in California were quick to recognize the need for protection against frost. Schoonover (45) reported 3,500,000 orchard heaters purchased by growers in the twenty-year period 1910-1930. California joined with the Weather Bureau to establish a Horticultural Protection Service under the direction of F. D. Young in about 1912. Growers recognized that forecasts and a better understanding of weather conditions related to frosts and freezing were necessary to successful protection. Considerable work followed in this field in California.

One of the early investigators to study the records of nights when frosts threatened was McAdie (39). He pointed out the effective mixing of a stratified layer of warm air from above by wind as a frequent frost deterrent and suggested mechanical mixing of air as a possible means of frost protection.

The stratification of air at night is described in some detail by Humphreys (36) who recognized the value of wind in mixing the lower atmosphere to prevent excessive cooling of the earth's surface. Mechanical mixing would give results similar to wind if on a sufficiently large scale according to Humphreys, but he stated that this was "clearly out of the question as a commercial proposition."

Early workers in California and Oregon quickly recognized that frost protection was directly correlated with the depth and strength of the nocturnal inversion layer. Nocturnal inversions or an increase of air temperature with height instead of the normal decrease were observed by many workers. The stratification of a warm layer of air above the orchard acted as a ceiling making possible the warming of the air down into the orchard by the use of heaters. Where protection was obtained from air drainage it was the warm air from above that moved into the grove replacing the cold air as it drained down slope from the grove. As a result, much work was done on measuring inversions and many articles were written on the subject. Young (53) goes into some detail on how inversions are formed along with reporting observations of inversions at Pomona, California, and Medford, Oregon. Geiger (28) explains in detail the formation of

nocturnal temperature inversions in Chapter 4 of his book. An understanding of this phenomenon and detailed investigation of inversion patterns within an area for several years are necessary according to Young (55) because inversions vary as does weather.

The idea of mechanically mixing the untapped reservoir of warm air known to be above orchards on many cold nights continued to intrigue growers. Young (55) reported in 1929 that no machine affording practical protection had been developed. In 1938, just nine years later, Young (56) reported 133 wind machines in operation in California. At the same time, he reported 4,075,248 heaters of all types in operation in California citrus groves.

Moses (40) reported 150 wind machines in use in California in 1938. He cites benefits of up to 3°F from blowers. He concluded that a blower of 75 horsepower or greater mounted on a tower 40-50 feet above the ground would maintain 3°F protection over 10 acres with a 10°F inversion up to 100 feet.

Schoonover et al. (44) gave a brief account of wind machine use in 1939 and listed small machines as being effective over a 300-foot radius and large machines over a 500-foot radius. They suggested that wind machines should be turned on as soon as temperatures dropped as low as 32°F.

Although most of the first work with wind machines was done by pioneering growers, the University of California, Division of Agricultural Engineering, started intensive studies on frost protection

methods including wind machines in 1937 (10). By 1951, under the impetus of doubled fuel costs for heating after World War II, public animosity over smog created by heaters, and availability of improved types of wind machines, there were more than 2,800 wind machines in California (11).

Brooks et al. (12) reported in 1948 that wind machines offer protection against light radiation frosts. Temperatures can be raised by 1 to 2°F but the natural cooling process is not stopped. In one of the three tests reported, a 3°F temperature gain was registered 250 feet upwind and almost a 2°F response was noted 750 feet downwind, which indicated wind machine protection patterns to be strongly affected by air drift. Brooks also recommended that wind machines not be started until temperatures have approached the danger point. The recommendation has its basis in the fact that wind machines add no appreciable heat and the entire gain will come from the air mixing or forced convection.

In 1950 Yarick (52) reported the protection pattern of wind machine trials to be shaped like a doughnut. He found operating costs on wind machines to be less than the costs of firing heaters but protection to be somewhat limited. Yarick claimed an apparent protection pattern for the wind machine when there was no evidence of temperature rise on thermometers. He explains this phenomenon by the forced circulation reducing air temperature differences at various levels in and among the trees.

Brooks et al. (9) reported in 1951 that significant responses from wind machines depend more directly on temperature inversions

than do those from heaters. They also advanced the assumption that wind machines are probably more sensitive to variations in air drift velocities than are heaters.

In 1952, Brooks et al. (14) reported that large 90 brake horsepower (bhp) machines take full advantage of a large inversion (6 to 12°F) whereas the small 15 bhp machines do not. They made measurements with the propeller blade having a $7\frac{1}{2}^{\circ}$ downward pitch and concluded this to be about the best angle. Increasing the propeller angle gave a greater temperature response but over a smaller area. In these tests, four machines spaced to give overlapping patterns complemented each other and provided protection for a larger area than the cumulative area of four machines spaced independently of each other. The area immediately around the tower of the wind machine received little protection. In this paper, the authors stated that the wind machine propeller sets in motion a stream of air that is actually a free jet until it reaches the tree tops. The outline of the jet is a cylindrical cone with the propeller located in the cone about three propeller diameters from the apex. The included angle of the cone is about 24° and is independent of the origin of the jet. The cross sectional area of the jet increases directly as the square of the distance. It was concluded that a free jet is a good mixing device since the increase in volume rate of flow must come from the surrounding air, which is drawn into and mixed with the rest of the jet. The authors stated that the force of

the jet was equal to the thrust of the propeller and that this made thrust the most significant measure of jet effectiveness.

Further tests reported in 1953 by Brooks et al. (15) confirmed the complementary action of two or more wind machines spaced to permit some overlapping of patterns. In these tests studies were made on the effect of choice of propeller design and diameter. It was concluded that the propeller diameter should be as large as practical with the reduction gears added to give the low-speed, high-torque drive required. The optimum design seemed to be two blades of sheet metal construction. The best blade design should be rather narrow for its length, have a moderate amount of taper toward its tip, and should have a low-cambered, low-drag airfoil section. A report was also made on tests with a wind machine using a vertical shaft, three-blade helicopter design. The blades were pointed upward about 45° above the horizontal. This machine gave a remarkable 8°F response at the base of the machine with a 12°F inversion, but the 2° response line only covered three-fourths of an acre. This machine also produced a 4°F rise in temperature at the base of the machine in a weak 6°F inversion but had about half the area showing a 1°F temperature rise when compared with the same temperature response with the 12°F inversion. Investigations of the physical barriers in the orchard revealed a sharp angular up-flow of the warm air over the cold orchard air about 50-70 feet from the machine.

Progress reports on wind machine tests made by Brooks et al. (16) in 1954 review some previous work on desirable spacings for

multiple installations of wind machines. They recommended that small wind machines (15 bhp) be spaced 400 feet apart transverse to the line of cold air drift and 550 feet apart in line with the drift. Large machines (70 bhp or larger) should be spaced about 700 by 900 feet.

Baker (6) stated that the ability of the wind machine to provide protection depended on the existence of warm air above the orchard. The author first analyzed the action of a wind machine and correlated it with the theory of the free jet. In the analysis of a stationary jet, the author brought out the important concept of air entrainment by the expanding jet. He stated that when new air is drawn into the jet to make up its expanding bulk, the new air is drawn into the jet all along the cylindrical periphery of the slice. The theoretical thermal response at a point in the protected area of the orchard was about 35 percent of the difference in air temperature at wind machine height and orchard air temperatures. The author emphasized that actually temperature distribution was far from uniform and that the presence of trees altered the flow.

Reports on wind machine trials in deciduous orchards by Rhoades et al. (42) indicated the wind machine to be much less effective than it had been with trials in citrus. On 16 test nights inversions averaged about half what had been found in previous tests with citrus. During a cold period growers in the area received complete protection for blossoms from 20 or more heaters per acre

whereas the wind machine alone provided about 25 percent protection for the same conditions. The authors recommended that a study of inversions be made in an area prior to investing in a wind machine for frost protection.

Tests were continued in deciduous orchards in 1956 by Brooks and Leonard (13). Weak inversions again reduced the effectiveness of the wind machine to a point that was almost valueless. They recommended the use of the wind machine in combination with heaters under such conditions. Preliminary tests were reported on a ramjet-rotor wind machine. It appeared to be worthy of further investigation because it provided both air mixing and a source of heat.

Some work was reported by Brooks et al. (17) in 1950 on the use of wind machines in combination with heaters. The experiment included about 20 acres. They concluded that using heaters and wind machines in combination showed a 20-30 percent gain in temperature response over that obtained when wind machines and heaters were used separately.

Crawford and Leonard (22) tested wind machines in combination with heaters for frost protection in deciduous orchards in 1960. They reported that much heat added near the wind machine gave bouyancy to the jet and lifted it out of the orchard. Evenly distributed heaters burning at low rates of fuel consumption offered some promise but needed further testing. Results were also reported on the use of border heat. Heaters were placed in rows 330 feet from the wind machine to form a square border. Using this pattern, the best

temperature responses were in the heater border row and relatively near the wind machine. One interesting observation made by these men was that without natural wind to help along air turbulence created by the wind machine, the wind machine could not be so effective.

Further tests were made in deciduous orchards with a conventional gasoline-powered 75 bhp wind machine and with the ramjet-rotor machine in the winter of 1956-57 (32). Inversions continued to be generally weak but performance on one night with an 8°F inversion compared favorably with protection obtained with machines in citrus where similar inversions occurred. The ramjet-rotor machine had a propeller 23 feet in diameter, with a ramjet engine mounted on each end. The propeller hub was mounted on a tower 36 feet above the ground. The propeller gave 1100 pounds thrust downward at a 15° angle. The blade rotated at 550 RPM. The head of the power unit rotated 360° in six minutes. The ramjet-rotor gave a remarkable 7°F response with a 7.5°F inversion over a small area. A 2°F response was recorded for 8.1 acres as compared with a 6.9-acre area for the conventional gasoline-engine-powered machine. It was quite apparent that the ramjet-rotor propeller was successful in pulling the heat generated by the engines into the jet created by the propeller. This extra heat was then successfully mixed with the orchard air over a large area. The designers of this machine had intended to obtain results similar to the use of wind machines in combination with heat

without the additional labor. The tests indicated some measure of success on this objective but called attention to two serious disadvantages: (a) fuel consumption which was 96 gallons per hour - enough to burn 150 to 200 heaters, and (b) noise enough to be quite objectionable except in the most isolated areas. In these tests, Goodall and associates called attention to the effects of winter cover crops in deciduous orchards on cold protection. The tall cover crop definitely reduced the wind machine response in lower parts of trees and was serious enough to cause fruit losses in these parts of trees.

In 1958, Brooks and Schultz (18) reported on comparative costs for protection from wind machines, heaters, and combinations of the two. Operating costs for heaters alone for 50 hours protection were \$100 per acre. Operating costs for wind machines alone with occasional heater support were \$38 per acre. Initial investment costs were \$450 per acre for the wind machine plus 15 heaters as compared to \$340 per acre for 50 heaters. They also reported that the area in which overhead warm air was effectively mixed with chilled air in the tree zone depended on tower rotation time as well as propeller thrust. The turning time recommended for the machine was once in eight minutes for a dual propeller 70 bhp machine. They recommended the use of heaters in combination with wind machines for the added protection, and indicated that the heater hours of support when needed amount to less than one-sixth those needed without the wind machine.

Preliminary tests on an under-tree wind machine as contrasted with conventional tower models were reported by Crawford and Brooks (21) in 1959. The area protected on two nights seemed to be roughly between that protected by the small (25 bhp) conventional machine and the large (75 bhp) dual-propeller machine tested under similar conditions. Heat added to the source of the under-tree machine by two large propane burners proved ineffectual. The temperature was raised over one-tenth of an acre but additional protection was lost due to the bouyant jet rising out of the orchard.

Leonard (37) gave an analytical explanation of wind machines as turning jets. He stated that the jet can best be described as an expanding toroid. The analysis combined the laws of a stationary jet and those of the expanding toroid into a single set of equations. There was a tremendous lag by the out-flowing air behind the axis of the propeller as the machine turned. As the wind machine made one complete revolution the new jet envelope was created inside the previous one and eventually made contact with the preceding one outside of it. At this point, the jets had to merge rather rapidly according to Leonard.

Much of the work done in California on wind machines and other means of frost protection is summarized in a text on physical microclimatology prepared by Brooks (8) and published in 1959.

Experiments on wind machines were begun in Australia about 1950. In 1951, Angus (1) reported on some Australian field trials begun in 1947 and evaluated the California work. He concluded that

early trials with low-powered horizontal fans in Australia were most successful in sucking warm air from above but relatively inefficient at mixing the air and distributing it over a wide area. The California conventional design distributed and mixed air well but was less efficient at pulling warm air down from above. Detailed experiments with the large-blade (21 feet in diameter) low-powered rotor indicated a 2°F protection for .57 acres. Placing this on a comparable power basis with the conventional California model gave a power use of 13-15 bhp per acre protected for the Australian model as compared to 12 bhp per acre protected for the California conventional model.

In 1952, Angus (2) reported further tests in which an average of 1.24 acres of 2°F protection was obtained for the fan tilted at 62° . A maximum rise in temperature of 6 to 6.5°F at various tilts with inversion strengths of 7 to 9°F was reported. The power used was about 8 bhp per acre. The head on the wind machine was rotated 360° in one minute for the most efficient operation as compared to a rotation once in three minutes.

Further experiments reported by Angus in 1956 (4) indicated that the optimum degree of tilt lies between 70 and 80° . He also indicated that the area to be protected varies as the cube root of the power consumption. Work has begun on a ducted machine design that offered promise for minimizing buoyancy effects. He concluded that a distribution of small machines would give a better and more consistent performance than one large unit.

The Federal-State Frost Warning Service started some field trials of wind machines in Florida about 1953. These trials were in cooperation with a grower and under the direction of J. G. Georg, Field Meteorologist for the Bartow District. In the 1957-58 Season's Report (30), Georg concluded that wind machines provided some protection on cold nights. Since these trials were carried on primarily in citrus nurseries, measurements were made at 18 inches and the wind machine was operated with supplemental heat on critical nights. It was interesting to note that Georg reported a 6.5°F inversion as the largest noted in the very cold 1957-58 season. In Georg's conclusions he stated, "Experience has shown that benefits of the wind machine extend beyond retarding the rate of temperature fall or actually raising the temperature at the level of concern."

Further field trials reported in the Frost Warning Service's 1958-59 Season's Annual Report by Georg (31) were conducted both in a nursery and in a mature grapefruit grove. Although some definite benefits were observed from the wind machine operating in the mature grapefruit grove, Georg reported that on a few occasions the stability of the air to tree height was most difficult to break down. This could be due in part to the roughness factor created by the tall trees but the author suggested that another parameter in addition to temperature had an important effect on the machines' ability to mix the air. This parameter was, according to Georg, air density. It should be noted that Georg's work in a mature citrus grove was with a 25 horsepower electric model wind machine.

A study of frost protection could not be complete without some understanding of air drainage. Marvin (38) gave an excellent treatise on air drainage, and explained how air drainage differs from water drainage.

Thornthwaite (47) said that an extremely important theme in microclimatology was the role of mixing in the air layer near the ground.

Halstead (33) stated,

...the drag of the wind over a horizontal surface usually referred to as the surface shearing stress has a direct part in those problems of climatology and meteorology that deal with atmospheric motion. Indirectly, interest in the shearing stress may be even greater, for since it can be interpreted as the rate of transfer of horizontal momentum from the atmosphere to the ground, it is involved either explicitly or implicitly in almost all work on turbulent transfer of heat or water vapor as well.

Halstead and Covey (34) indicated that the mixing expressed as a coefficient of diffusion, or Austausch coefficient, did not depend on the wind speed, but upon the rate of change with height of the wind speed. They proposed a mathematical model for convective heat transfer as:

$$q_{\text{conv}} = -1/3 \rho C_p V_c / V (U_{2z} - U_z) (T_{2z} - T_z)$$

where:

q_{conv} = convective heat flux (cal/cm² sec)

ρ = density of air (about 0.0012 g/cm³ @ N.T.P.)

C_p = specific heat of air (about 0.24 cal/g deg. @ N.T.P.)

V_c = thermal conductivity of air (about 0.21 cm²/sec @ N.T.P.)

V = viscosity of air (about 0.15 cm²/sec @ N.T.P.)

U_z = wind speed at height z

T_z = temperature at height z .

An explanation of the braking effect ground cover has on wind near the surface is given in Chapter 28 of Geiger (29). The height of plant cover where the wind is retarded is known as the "roughness height" and is the height where plant cover turns the wind in other than its prevailing direction. In extreme instances there may even be a reversal of wind direction close above the plant leaves. The vegetative cover and "roughness" height can have considerable influence on the turbulent mixing of air near the surface. In Chapter 32 of his book, Geiger (29) reported on measurements made of winds in oak forest trees before and after the trees had leafed out. Measurements were taken for 206 hours before the trees leafed out and for 494 hours after leafing out. The results of the braking effect trees with foliage and without foliage had on wind are shown in Table 1.

TABLE 1

THE EFFECTS OF LEAF DEVELOPMENT ON THE DISTRIBUTION OF WIND
SPEED IN AN OAK GROVE*

Height Above the Forest Floor in Meters	Position of Anemometer	<u>Percentage of Calm Hours</u>	
		Before Leafing	After Leafing
27	Above the Crown	0	10
24	In the Crown	8	33
20	Lower edge of Crown	35	86
4	Above forest floor	67	98

*R. Geiger (29).

Any work done on frost protection must include a study of the way frost forms and the formation of nocturnal inversions. Young (55) and Humphreys (36), a meteorological physicist, gave excellent summaries of the physical laws involved in the formation of frost and in the development of nocturnal inversions. Geiger (29) discussed long wave radiation and the formation of nocturnal inversions in Chapter 5 of his book. Other workers, however, have added to the store of knowledge so ably summarized by these pioneers in the field. Elsasser (26) emphasized the poor conductivity of free air in the absence of clouds. He found radiative cooling of free air to be on the order of 1°F per day for polar air masses and 2 to 3°F per day for equatorial air masses. Elsasser found no indication of radiative heating of air. On long wave radiation, the atmosphere was found to be a cold source throughout the experiments. He concluded that apart from heat of condensation, all heat lost by radiation of the atmosphere must be supplied by turbulent exchange and convection.

Raschke (41) reviewed some of the basic laws and research relating to heat transfer between plants and the environment. He stated that plants act as black bodies according to the Stefan-Boltzman law of radiation, i.e., plants radiate heat with an intensity proportional to the fourth power of the absolute temperature. The boundary zone on leaves (thin skin of air adjacent to the surface in which heat transfer is through molecular heat conduction) may reach as much as one centimeter but tended to be much smaller. The boundary layer thickness increased with distance from the leaf margin. As a

result, large leaves may lose enough heat to have frost form on them when small leaves will be free of frost. Even though the extent of the boundary layer is small, the amount of heat exchanged in it may be large when there is constant air replacement. Heat transfer between a plant and its environment occurs essentially in three ways: through conduction and convection in the form of sensible heat; through the evaporation of water which includes condensation, freezing, thawing, and sublimation in the form of latent heat; and through radiation in the form of radiant heat.

Curtis (23) measured leaf temperatures cooled by radiation and reported orange leaves cooler than ambient air by about 10°F.

Curtis et al. (24) found that air is largely transparent to radiation and its temperature does not change rapidly with radiation intensity except as it is heated locally by absorbing objects such as leaves.

Wallace and Clum (49) claimed that leaf temperatures can be measured accurately by pressing thermocouples against a leaf surface and that it is not necessary to insert thermocouples in tissue. They asserted that many leaves receive radiation from the ground at night about as fast as they radiate to the sky and remained fairly close to air temperatures.

Wilson (51) reported that nocturnal cooling of leaves in arctic regions was of much smaller magnitude than warming during day time insolation. He found that wind continually changed the balance between leaf temperatures and air temperatures.

The strength of nocturnal inversions is important in frost protection now as it was in earliest work done in California by Young and his contemporaries. Turnage (48) reported that two-thirds of the nights in the Desert Laboratory, Tucson, Arizona, had pronounced inversions. He reported 9°F to be a common inversion, 15°F not unusual, and one inversion of 23°F. The inversions were measured up a hill to a height of 420 feet. Angus (5) found that inversion strengths weakened in the early morning hours. He also reported inversions averaging 6.9°F on five nights when temperatures fell below 34°F (3). Most inversions reported in Florida in the District Annual Reports of the Federal-State Frost Warning Service report differences in temperatures between high and low ground locations. Although these give indications of inversions, they do not indicate inversion strengths and the depth of inversions needed for frost protection. Some inversion measurements reported, however, do indicate that strong inversions may be present in Florida. Russell (43) reported in the Federal-State Frost Warning Service's Twenty Season Summary inversion measurements made on a tower near Lake Alfred. The inversion from the surface to 113 feet was 22°F. From the surface to 50 feet was 15°F. Summaries of temperatures at Gainesville for the 20-year period are given in Table 2. Similar differences in frequency of low temperatures and hours of duration between cold and warm locations are given for other frost protection districts in the state.

TABLE 2

COMPARISONS OF COLD AND WARM LOCATIONS SHOWING LOW
TEMPERATURE FREQUENCY AND HOURS OF DURATION

Temperature	Cold Locations	Warm Locations
32° and lower	400 times for 2,000 hours	200 times for 2,000 hours
28° and lower	200 times for 1,000 hours	100 times for 400 hours
24° and lower	75 times for 300 hours	20 times for 50 hours

III. EXPERIMENTAL METHODS

Plot Description

This research work was carried out on the Florida Agricultural Experiment Station Horticultural Unit about ten miles northwest of the main campus, University of Florida, Gainesville, Florida. The areas designated as test and check plots were a part of the Horticultural Unit under the jurisdiction of the Fruit Crops Department.

The test plot and check plot were each about ten acres in size and were contiguous. Each plot represented a standard ten acres, i.e., 660 feet by 660 feet. The topography of the experimental area is generally level with a gentle slope to the south. The extreme southwest corner of the test area drops off with a little more than a 3 percent slope to the south-southwest. The size, shape, and relative positions of the research area are illustrated in Figure 1.

A brief description of the adjacent areas is given because of possible influence these areas might have on micro-climate of the research area. Across a paved road west of the test plot are the house, office, shops, and other buildings incidental to the operation of the Horticultural Unit. These buildings are beneath a broken canopy of native high hammock trees such as oak, hickory, and magnolia. Immediately north of the test plot are open fields assigned to the Vegetable Crops Department. These fields were frequently planted to winter cover crops such as oats or lupine during the test period.

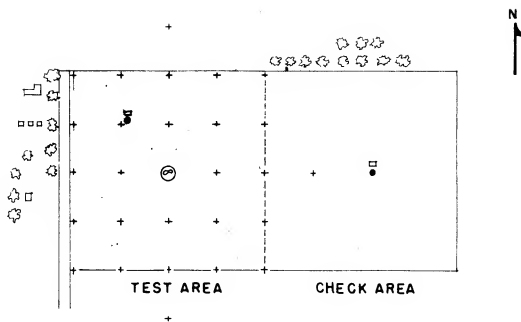


Fig. 1.-Plot layout, Horticultural Unit,
Gainesville, Florida

+ Temperature observation sites

⊙ Wind machine

• Inversion pole

□ Hygro-thermograph shelter

North of the check area is uncleared woodland except for the extreme northeast corner where there are experimental blueberry plots. East of the check area is cut-over pine land. South of the experimental area is a twenty-acre plot of Bahiagrass that formed a dense, brown cover 10 to 12 inches deep during the winter months.

The entire research area was devoted to plant breeding projects by research personnel in the Fruit Crops Department. Most of the test area and some of the check area were planted in peaches during the three seasons but the peach trees varied in size and planting density. Other fruits were also on the test area such as blackberries, grapes, pears, and persimmons. Orchard design including direction of rows and tree spacings varied over the area from year to year and within the same season.

Instrumentation

The research project was started in the 1958-59 season with a minimum of instrumentation. As funds became available, other instruments for measuring temperature differences and for obtaining additional information on cold protection were included in the project.

Wind machine

A Tropic Breeze GP-332 wind machine manufactured by National Frost Protection Co., Inc., Burbank, California, was installed in the center of the ten-acre test plot as indicated in Figure 1. Essential specifications for this machine as provided by the company are:

Engine...gasoline powered heavy duty Ford Industrial V-8,
90° overhead valve

RPM under load.	2,600
Fan RPM	590
Horsepower delivered to fan	85
Fan diameter.	15' 4"
Tower height to propeller hub	31'
Rotation time of fan head	.4-5 minutes

Recording inversions

A wooden pole of the type used by electric power companies was installed in both the test and check areas respectively. The relative locations of these poles can be seen on Figure 1. Each pole was just over 50 feet high.

Beaded thermocouples made of 24-gauge copper-constantan wire were installed on each pole at the 1, 5, 9, 15, 20, 25, 30, 35, 40, 45, and 50 feet levels respectively. Each thermocouple was shielded from the sky by a simple shield similar to that used for grove thermometers.

The thermocouples on the pole in the test area were tied into a Minneapolis-Honeywell Brown "Elektronik" twenty-point recorder. The thermocouples on the pole in the check area were read with a portable, manually-balanced potentiometer. The check area did not have electric power available to it.

Temperature recording network for ambient air temperatures

Measurement of temperature differences formed a major means of evaluating results.

A grid of temperature observing stations was set up in the area. The grid was made up of 25 observation sites arranged 165 feet apart on a five by five square. See Figure 1. Each station had minimum recording thermometers at 1 and 5 feet. A copper-constantan thermocouple was installed at the 9-foot level. Both thermometers and the thermocouple were shielded from the sky.

Stations identical with those in the grid were placed north, east, and south of the grid respectively. No station was placed west of the grid because of the Horticultural Unit buildings in the area.

Thermocouples were read for the first two seasons at each of the stations with the manually-balanced, portable potentiometer. The thermocouples in the grid were tied together and connected to an automatic balancing potentiometer in the third season. Pint and one-half pint thermos bottle fillers were tied to the thermocouple and network junction at each station. These were filled with ice and water before each test night to serve as a standard reference point.

Two hygro-thermographs were located outside the experimental area the first season and were used primarily for temperature comparisons. In the second season hygro-thermographs in standard Frost Warning Service shelters were placed at the base of the inversion measuring poles in the test and check areas respectively.

Tissue temperature measurements

Leaf temperatures were measured by three types of thermocouples tied into the Brown twenty-point "Elektronik" recorder.

Soldered thermocouples and beaded thermocouples made of 32-gauge copper-constantan wire were used for different leaf temperature measuring techniques. Solid-strip copper-constantan thermocouples were made from .003 inch thick copper and constantan bonded together into strips or ribbons .25 inch wide. The strip thermocouples were about 1 inch long.

Tissue temperatures taken beneath the bark of peach trees were measured with beaded copper-constantan thermocouples tied into the Brown "Elektronik" recorder.

Calibration

Minimum thermometers were all calibrated in a melting ice bath against a standard thermometer.

Thermocouples used in the Brown "Elektronik" recorder were checked in the melting ice bath against a standard thermometer and at room temperature with the manually-balanced potentiometer. The thermocouples were also tied into the recorder and checked against the standard thermometer in a walk-in freezer-type box down to 20°F.

The hygro-thermographs were constantly checked against minimum thermometers that were calibrated and the two hygro-thermographs were run together over a period of several weeks and adjusted to read together.

No adjustments or calibrations were made on the wind machine.

Wind and air drift measurements

No provision was made for measuring wind direction and velocity in the first season. All winds recorded for the 1958-59 season were estimates of the observer.

An anemometer was installed in the building area just outside the test area for the 1959-60 season but was moved to the top of the test area inversion pole for the 1960-61 season. A sensitive anemometer was borrowed for the 1960-61 season which provided an excellent means of detecting light wind drift but would not permit measurement of total wind travel as intended because of a defective recorder.

A helium-filled captive weather balloon was used to observe wind drift on some nights. Very light-weight nylon yarn was tied to a 120-foot thin nylon anchor line at intervals of 5 feet to observe air turbulence at varying levels.

Heaters

One hundred thirty lazy-flame stack heaters, fuel storage facilities and a tank trailer for distributing fuel were added to the project in the 1960-61 season.

Methods and Techniques

During the 1958-59 season and the 1959-60 season temperatures were observed by following a regular pattern through the entire network every other hour. The pattern terminated with a measurement of the check pole inversion. The total time required to take temperature readings varied between 45 and 60 minutes. This method was discarded in the 1960-61 season in favor of the automatic recording of temperatures at the 9-foot level. A switching device on the recorder made it possible to read temperatures at all stations in about five minutes.

Minimum temperatures were recorded from thermometers at the 1 and 5 feet levels after each test night.

In the 1958-59 season, the wind machine was operated when temperatures dropped below about 34°F. The wind machine was operated on nights when there was little or no inversion in the first and second seasons as well as on nights considered to be good test nights. In the 1960-61 season some criteria verified in the previous seasons were used to determine when to run the machine. These criteria were: an inversion present, clear, wind less than 5 mph, and temperatures expected to be critical for frost.

Inversions were measured in both the test and check areas before starting the wind machine. The Brown recorder was allowed to run while measuring inversions by hand at the check pole. This permitted comparisons of inversions in the test and check areas for about the same time. Inversions were measured periodically at both points throughout a test night.

Tissue temperatures were measured beneath the bark of peach trees in the 1960-61 season. Thermocouples were made by welding 24-gauge copper-constantan wire. The resulting bead was then carefully ground down with an electric emery wheel as thin as possible without seriously weakening the union. These thermocouples were inserted into the cambium area of varying sizes of peach limbs. The thermocouples were held in place by rubber grafting bands below the point of the thermocouple and the wound resulting from inserting the thermocouple was sealed with a mixture of paraffin and beeswax. Similar

thermocouples were inserted in a few Rusk citrange seedlings. All thermocouples were read with the Brown recorder.

Peach leaf temperatures were measured after the 1960-61 danger of cold had passed and the peach trees had fully leafed out. These temperatures were measured on a radiation night with and without the wind machine operating. Several techniques of measuring leaf temperatures were used.

(a) Beaded 32-gauge copper-constantan wire thermocouples were inserted in leaf tissue.

(b) Soldered 32-gauge copper-constantan wire thermocouples were threaded in leaves.

(c) Strip copper-constantan thermocouples were fastened tightly to the under surface of leaves.

(d) Strip copper-constantan thermocouples were folded in leaves.

All methods were compared with measurements of ambient air temperatures.

Peach leaf temperatures were measured under controlled conditions in a climate chamber using the same techniques as described above. Radiation effects were simulated with an insulated box covered with clear polyethylene.

Turbulence patterns of air created by the wind machine were systematically observed by anchoring a helium-filled captive balloon at known points over the entire test area. Attached to the anchor line were nylon yarn streamers at 5-foot intervals. These streamers

were observed by shining a light along the anchor line. The movement and patterns formed by yarn movement were recorded in relation to wind machine position for each point where the balloon was anchored.

Heaters were lit in several patterns to supplement protection by the wind machine toward the last of the 1961 season. Every other heater was lit on a distributed pattern giving about ten heaters to the acre on one night. Heaters were lit along the borders and in cold spots toward the periphery of the protected area a second night.

IV. RESULTS AND DISCUSSION

Plot Comparisons

Many references were in the literature to the extreme variability in climatic factors that affect plants even in a small area. Brooks (8) and Geiger (29) both called attention to the influence of soil types, plant cover, slope, and other topographic features that may drastically affect the climate near the ground.

Since differences in temperature were to be a major means of evaluating results, it was quite important that the plots selected be as uniform as possible and that those features in the plot having undue influence be identified. This was particularly important since budget limitations made it impossible to replicate the plots and analyze the data statistically. In view of this, a careful study was made of temperatures recorded at the various stations on several nights when no protective measures were applied. Figures 2 and 3 represent analyses made of two such nights. Stations 5 and 28 were consistently colder than other stations in the area. The entire south end of the plot tended to be colder than the rest of the area. The remainder of the area was fairly uniform for temperatures at the 5-foot level on all nights checked. Station 26, located across the road in the vegetable area and outside the station grid system, had temperatures similar to those in the test area when no protection was provided. This same station was in close agreement with

Information pertinent to minimum temperature
isotherms shown in Fig. 2

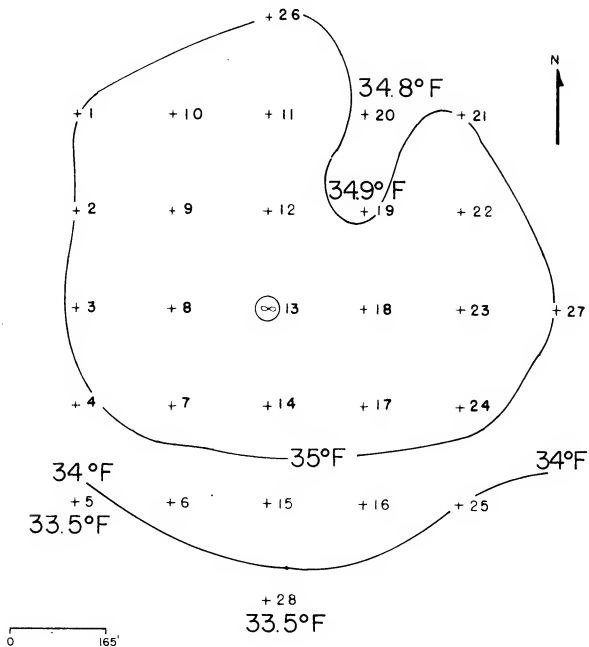
Cloud cover: Clear

Wind: Calm

Maximum inversion: + 4°F

Check area minimum temperature: + 35°F

Wind machine: Not operating



MINIMUM TEMPERATURE ISOTHERMS
AT THE FIVE FOOT LEVEL
February 10, 1961

Fig. 2

Information pertinent to minimum temperature
isotherms shown in Fig. 3

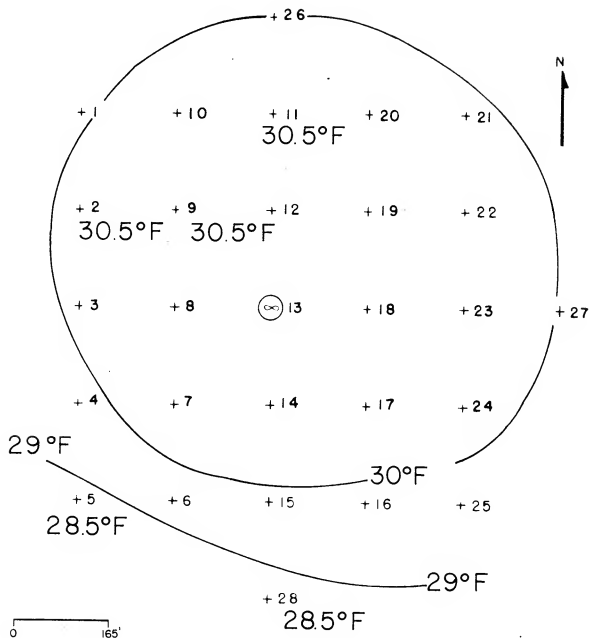
Cloud cover: Clear

Wind: West 2-4 mph

Maximum inversion: + 1.5°F

Check area minimum temperature: + 30.5°F

Wind machine: Not operating



MINIMUM TEMPERATURE ISOTHERMS
AT THE FIVE FOOT LEVEL
February 16, 1960

Fig. 3

hygro-thermographs located outside the test area on test nights. This station was never observed to be influenced by the wind machine when in operation and since the temperatures at the 5-foot level agreed closely with the check thermographs, isotherms running through the station have been used as base lines for determining degrees of protection received. Low temperatures at stations 5, 28, and others on the extreme south end of the plot could not be used to indicate the total degrees of response from wind machine operation since these stations were down-slope and were consistently colder than the remainder of the stations on nights when the wind machine was not operating.

The hygro-thermographs placed in the test and check area gave very close agreement on temperatures for many nights when no protective measures were taken.

Inversions were checked at both poles for exactly the same time by allowing the Brown Electronik recorder to run while the inversion was read manually at the check pole. A simple projecting of time on the recorder chart gave a simultaneous comparison of inversions. Table 3 gives an indication of the agreement between inversions in the test and check area. Differences observed were no greater than possible errors in reading of instruments.

The information obtained indicated a fair degree of uniformity in the area. It did indicate a build up of cold air on the south end of the plot and that temperatures at these stations could not be considered as base temperatures when comparing results of protective measures.

TABLE 3

COMPARISON OF INVERSION TEMPERATURES MEASURED AT TEST AND
CHECK POLES FOR THE SAME TIME PERIOD

Date	Time	Test Pole*	Check Pole*	Temp. at 5' in °F	Height in Feet of Maximum Temperature
1/5/59	9:30 a.m.	+ 4.0°	+ 4.0°	37.0	45
1/13/59	12:30 a.m.	+11.0°	+10.8°	34.0	40
1/24/59	2:30 a.m.	+ 2.0°	+ 2.0°	41.5	50
2/22/59	12:30 a.m.	+ 5.5°	+ 5.3°	41.5	45
3/3/59	12:40 a.m.	+ 4.3°	+ 4.1°	39.5	50
3/9/59	3:40 a.m.	+ 4.0°	+ 4.0°	37.5	45
2/8/60	4:30 a.m.	+ 4.0°	+ 4.0°	36.5	45
2/13/60	10:00 p.m.	+ 4.0°	+ 3.9°	34.0	50
2/14/60	10:00 p.m.	+ 3.0°	+ 3.0°	35.0	45
2/19/60	3:50 a.m.	- 2.0°	- 2.0°	33.5	05
2/20/60	12:20 a.m.	+ 5.0°	+ 5.2°	32.5	45
2/27/60	3:30 a.m.	+ 3.0°	+ 2.8°	34.0	50
3/4/60	3:00 a.m.	0	0	35.0	05
3/4/60	9:00 p.m.	+ 5.0°	+ 4.9°	34.0	45
12/17/60	8:00 p.m.	+ 6.5°	+ 6.4°	32.5	50
12/19/60	8:00 p.m.	+ 7.5°	+ 7.7°	38.5	50
12/23/60	7:00 p.m.	+ 3.5°	+ 3.5°	35.5	50
2/5/61	2:00 a.m.	+ 3.0°	+ 3.0°	36.5	45
2/11/61	4:30 a.m.	+ 4.5°	+ 4.7°	34.5	45
2/26/61	1:15 a.m.	+ 1.5°	+ 1.5°	47.0	45
3/10/61	2:00 a.m.	+ 2.0°	+ 2.0°	38.0	45
3/11/61	1:30 a.m.	+ 9.9°	+ 9.7°	38.5	45

*Inversions measured to a height of 50 feet. Inversions read before wind machine was started.

Instrumentation

Temperature readings on standard Weather Bureau minimum thermometers provided one of the more reliable sources of data during the tests. Temperatures recorded at the 5-foot level were fairly consistent and were used to construct minimum temperature isotherm charts to show both the degrees of protection and size of area protected. These charts will be discussed in some detail later in this chapter. Temperatures taken from the thermometers at the 1 foot level were most erratic and could not be used in a complete analysis. Apparently these thermometers were close enough to the ground to be influenced by the type of ground cover. The ground cover under these thermometers varied from clean sand to dense brown grass. Temperatures varied from considerably colder than the 5-foot level to about 2°F warmer. A serious problem with the type thermometer used was the ease with which alcohol separated in the glass tube. There would often be several thermometers separated during a test night. Temperatures for that level and station were missing. This condition is represented by a dash in the Appendix tables. The 1959-60 season was started with fewer thermometers than station positions. As a result, the 1 foot level on a few stations located the greatest distance from the wind machine was without a thermometer. This condition was corrected for the 1960-61 season.

The original plan of the experiment called for the temperatures to be recorded at the 9-foot level with a manually-balanced, portable potentiometer. A standard pattern was followed in taking readings to

give about the same time lapse between successive readings. During the first season it became obvious that this plan was impractical for several reasons. The potentiometer used a standard reference cell that had to be maintained above 32°F for correct operation. On very cold nights, the potentiometer would fail to balance properly before getting half through the temperature recording stations. When temperatures were at or near freezing, readings could be obtained satisfactorily but even these were very erratic and difficult to analyze. This was because temperatures fluctuated rapidly with wind machine passage at the 9-foot level and because it was impossible to obtain readings close to each other in a time sequence.

In the 1960-61 season all 9-foot level thermocouples within the grid were tied together in a network. The network was tied through a switching system into a recorder. With this system, all stations could be identified, read and recorded in about five minutes. Table 4 gives data obtained with the network. Values reported on December 24, 1960, may have been influenced by some heater trials in the area and cannot be compared with other readings listed at 9 feet. The network made it possible to follow wind machine passage at any station and observe temperature responses. This data will be discussed in detail and compared with minimum temperature isotherms for the 5-foot level on the same night. Considerable difficulty was experienced with broken wires in the network. February 11, 1961, was the last time to use the network as a harrow was run through the

TABLE 4

COMPARISON OF TEMPERATURES AT THE 9' LEVEL WITH
MINIMUM TEMPERATURES AT THE 5' LEVEL IN
DEGREES FAHRENHEIT

Station	12/24/60		2/5/61		2/11/61	
	9'*	5'	9'**	5'	9'***	5'
1	28.3	24.0	33.4	32.0	32.5	30.0
2	29.5	23.5	33.4	32.0	33.3	30.0
3	28.0	24.0	32.7	31.9	34.3	30.1
4	28.8	-	33.8	30.4	33.8	28.8
5	27.6	22.7	32.2	29.7	33.3	29.2
6	27.7	21.5	34.2	29.5	33.4	29.0
7	31.6	23.8	33.8	31.2	34.2	29.7
8	30.9	24.0	34.0	31.5	33.8	30.0
9	31.1	23.5	33.8	32.0	32.3	30.5
10	31.3	23.6	34.0	32.1	32.7	30.6
11	32.7	22.0	35.0	30.5	33.4	29.5
12	31.6	25.5	35.0	31.0	36.3	29.8
13	-	25.1	34.9	-	34.8	30.5
14	29.3	24.0	35.0	31.2	32.7	29.5
15	28.0	22.0	32.4	30.3	31.5	29.3
16	27.4	21.0	32.9	29.6	33.5	32.6
17	-	22.5	-	30.5	-	29.5
18	27.4	26.0	33.1	30.5	30.2	29.5
19	-	23.5	-	30.4	-	29.9
20	28.8	24.0	33.3	30.5	30.2	29.5
21	27.7	24.1	32.9	31.1	29.9	29.6
22	27.7	24.0	32.3	31.0	30.7	30.0
23	27.7	23.6	32.5	30.5	27.6	29.5
24	28.0	23.0	32.6	31.0	29.1	30.5
25	27.0	22.0	32.5	29.0	33.2	33.0

*Inversion +7.7°F, 3:30 a.m. Network Check.
9' temperature at check pole, 3:15 a.m. - 27.8°F.
Heaters under test with wind machine.

**Inversion +3.0°F, 3:15 a.m. Network Check.
9' temperature at check pole, 3:30 a.m. - 33.5°F.
Wind machine on.

***Inversion +5.1°F, 7:15 a.m. Network Check.
9' temperature at check pole, 6:40 a.m. - 32.5°F.
Wind machine on.

area and the network wires were cut in too many places to make repairs practical.

Hygro-thermographs installed in the area in the 1959-60 season gave some excellent charts for trend comparisons and to indicate total hours of cold present. Since there was only one hygro-thermograph in the protected area, the information recorded was good only for the point in the area where the hygro-thermograph was located. This instrument was also valuable in providing information on the dew point and relative humidity. The instrument was located about 260 feet northwest of the wind machine and showed very little direct response from wind machine operation before February 25, 1961. It is now known that the wind machine was seldom able to penetrate cold air drift to this point with the power setting at which the wind machine was operated. A change in power setting gave positive responses on the thermograph in the protected area. Figures 4 and 5 show this positive response.

An anemometer was not available during the 1958-59 season even though wind direction and velocity were known to be important factors. Brooks et al. (9) indicated wind machine effectiveness to be correlated with air drift velocity. An effort was made to estimate wind velocity and direction but subsequent information indicated the velocity estimates to be much too high. An anemometer was obtained and installed on the Horticultural Unit office building several hundred yards west of the protected area for the 1959-60 season.

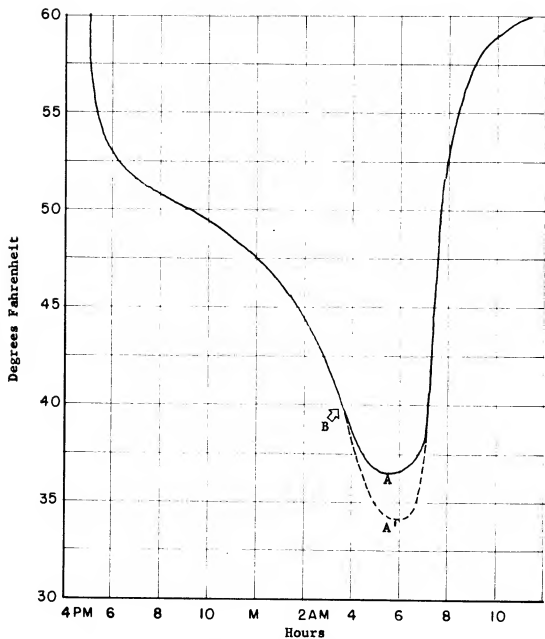


Fig. 4.-Temperature differences recorded on hygro-thermographs in the test and check areas - February 26, 1961

A - Hygro-thermograph reading - test area
A' - Hygro-thermograph reading - check area
B - Wind machine on

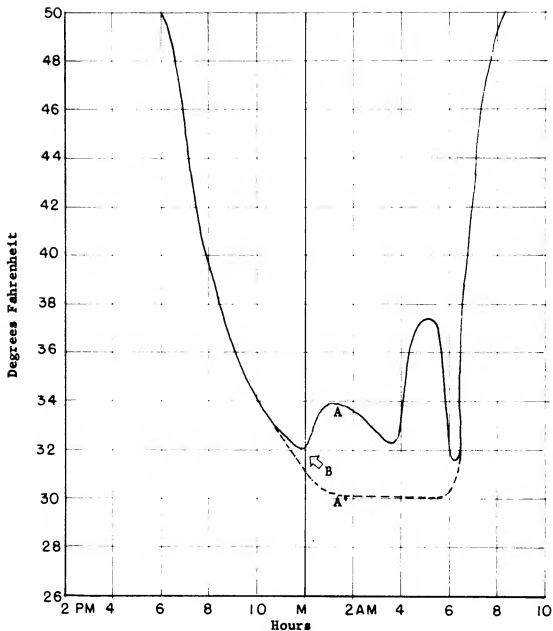


Fig. 5.-Temperature differences recorded on hygro-thermographs in the test and check areas - March 10, 1961

- A - Hygro-thermograph reading - test area
- A' - Hygro-thermograph reading - check area
- B - Wind machine on

The anemometer was helpful in picking up steady breezes of 2-4 mph or more. Brooks in Chapter IV of his book (8) stated that all plants, obstructions, and livestock projecting above the soil surface exert some force against air flow. The anemometer was moved from the building to the top of the inversion pole at the beginning of the 1960-61 season. The anemometer cups were at a height of approximately 55 feet. From this position, an excellent indication of winds that might give natural mixing of inversions was obtained. The best indicator of air-drift strength was the captive helium-filled weather balloon. The balloon indicated air-drift direction and something of its strength when the anemometer used was not sensitive enough to show air movement. Some sensitive anemometers were borrowed during the 1960-61 season from the Agronomy Department. They were quite sensitive to air movement but were of little value to the project since the recorder was inoperative and no measurements could be made of total air travel.

Wind Machine Trials

The wind machine described in Chapter III was tested as a possible source of frost protection over three seasons, 1958-59, 1959-60, and 1960-61. The amount of temperature response and the size of area affected by the response were used as primary means of evaluating machine effectiveness.

Figures 6 through 13 represent tests made in the 1958-59 season. As indicated earlier, wind direction and velocities were simply estimates and in view of additional information and experience, the wind velocity estimates made were too high. Wind estimates have been included with other pertinent data on facing pages opposite isotherm charts. A brief discussion of results of each night in the first season is given in the following paragraphs.

Protection patterns for January 6, 1959, are shown in Figure 6. Two degrees of protection were provided for an area of four to five acres.

Figure 7 represents protection patterns on the coldest night of the season. A weak inversion of 4°F was recorded about 3:30 a.m. This inversion did not hold throughout the night as there was considerable air movement. The general area temperature for the night was 20°F with an area of about four acres receiving 2°F protection.

The second night of the cold wave was fairly calm and the 14°F inversion was one of the largest inversions recorded in the three seasons. Two degrees of protection were obtained over about ten acres. Four degrees of protection were obtained in a small area around the machine. Figure 8 shows the protection pattern. The shift of the protection pattern to the east by prevailing air drift should be noted.

There was enough wind during the night of January 17 to effectively destroy most of the nocturnal inversion. The temperatures on the outside thermograph and at station 26 immediately north of the

Information pertinent to minimum temperature
isotherms shown in Fig. 6

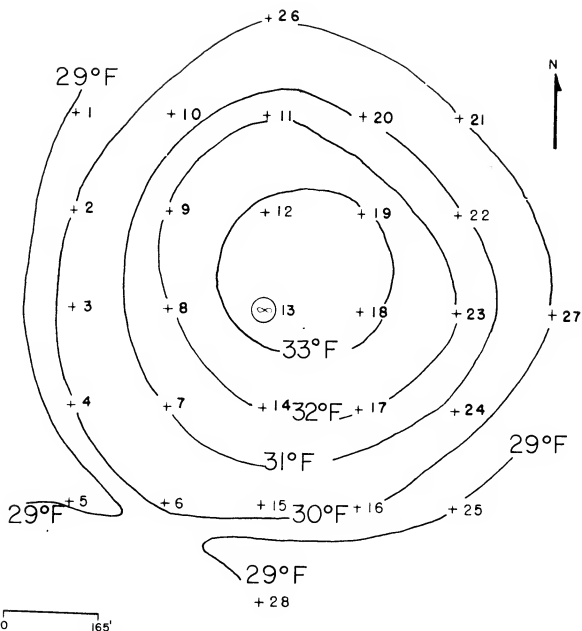
Cloud cover: Clear

Wind: NNW 3-5 mph

Maximum inversion: + 5.5°F

Check area minimum temperature: + 30.0°F

Wind machine: Operating at engine speed
of 2,600 rpm



MINIMUM TEMPERATURE ISOTHERMS
AT THE FIVE FOOT LEVEL
January 6, 1959

Fig. 6

Information pertinent to minimum temperature
isotherms shown in Fig. 7

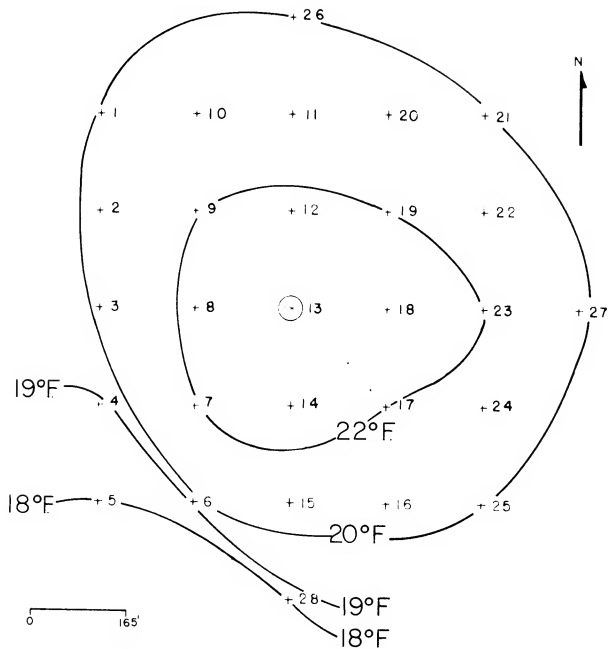
Cloud cover: Clear

Wind: W 5-10 mph

Maximum inversion: + 4°F

Check area minimum temperature: + 20.0°F

Wind machine: Operating at engine speed of
2,600 rpm



MINIMUM TEMPERATURE ISOTHERMS
AT THE FIVE FOOT LEVEL
January 12, 1959

Fig. 7

Information pertinent to minimum temperature
isotherms shown in Fig. 8

Cloud cover: Clear

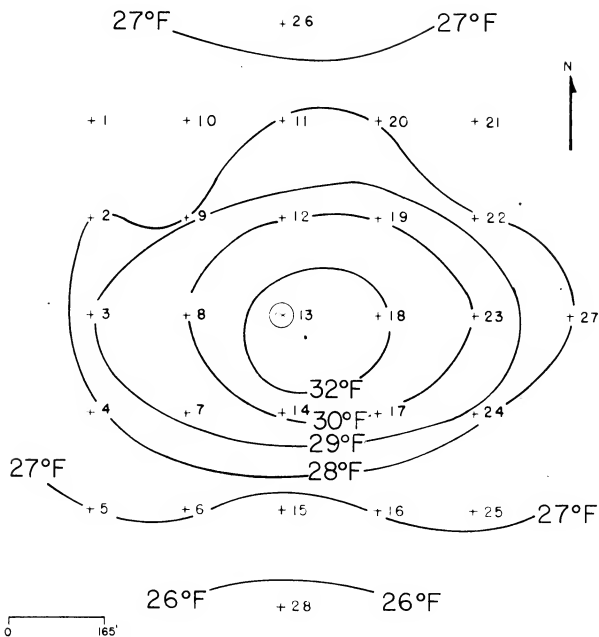
Wind: ENE 2-3 mph

Maximum inversion: + 14°F

Check area minimum temperature: + 27.0°F

Wind machine: Operating at engine speed of

2,600 rpm



MINIMUM TEMPERATURE ISOTHERMS
AT THE FIVE FOOT LEVEL
January 13, 1959

Fig. 8

Information pertinent to minimum temperature
isotherms shown in Fig. 9

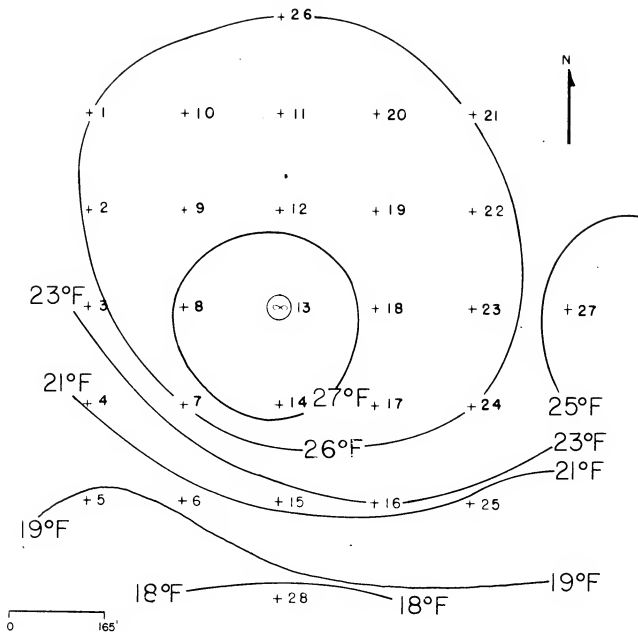
Cloud cover: Scattered, high drifting clouds

Wind: NNE 10 mph

Maximum inversion: 0.0

Check area minimum temperature: + 26.0°F

Wind machine: Operating at engine speed of
2,600 rpm



MINIMUM TEMPERATURE ISOTHERMS
AT THE FIVE FOOT LEVEL
January 17, 1959

Fig. 9

Information pertinent to minimum temperature
isotherms shown in Fig. 10

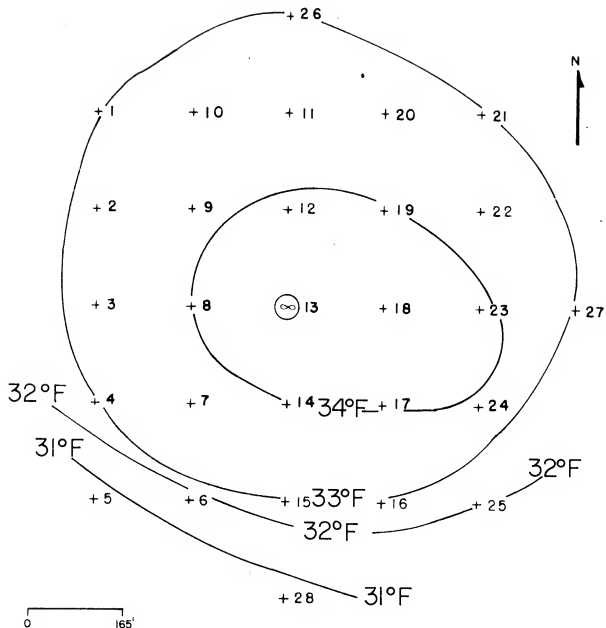
Cloud cover: Clear

Wind: W 5-10 mph

Maximum inversion: + 2.0°F

Check area minimum temperature: + 33.0°F

Wind machine: Operating at engine speed of
2,600 rpm



MINIMUM TEMPERATURE ISOTHERMS
AT THE FIVE FOOT LEVEL
January 24, 1959

Fig. 10

Information pertinent to minimum temperature
isotherms shown in Fig. 11

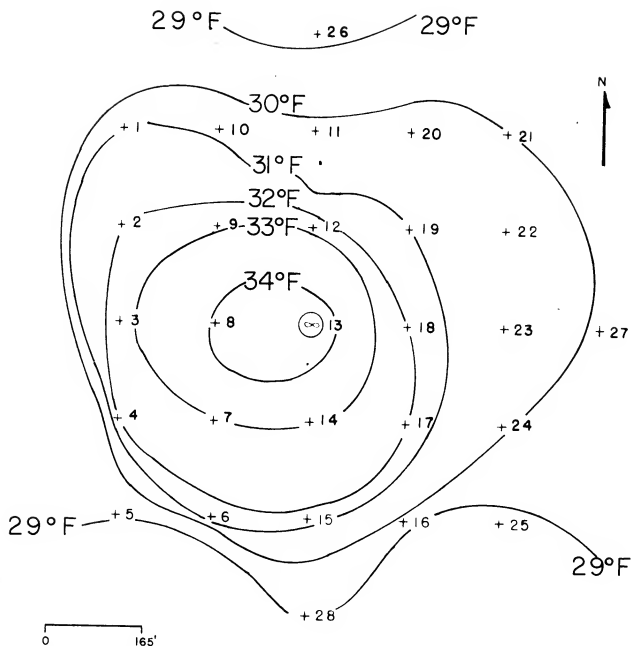
Cloud cover: Clear

Wind: NNE 0-3 mph

Maximum inversion: + 7.0°F

Check area minimum temperature: + 29.0°F

Wind machine: Operating at engine speed of
2,600 rpm



MINIMUM TEMPERATURE ISOTHERMS
AT THE FIVE FOOT LEVEL
February 22, 1959

Fig. 11

Information pertinent to minimum temperature
isotherms shown in Fig. 12

Cloud cover: Clear

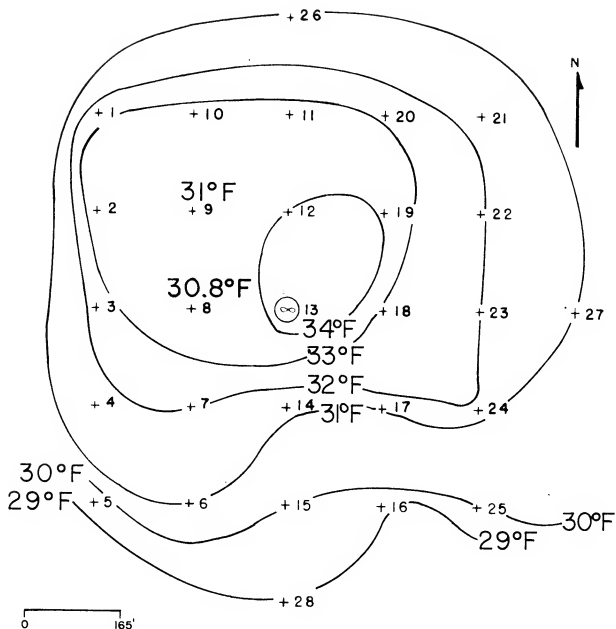
Wind: Variable 0-2 mph

Maximum inversion: + 5.0°F

Check area minimum temperature: + 31.0°F

Wind machine: Operating at engine speed of

2,600 rpm



MINIMUM TEMPERATURE ISOTHERMS
AT THE FIVE FOOT LEVEL
March 3, 1959

Fig. 12

Information pertinent to minimum temperature
isotherms shown in Fig. 13

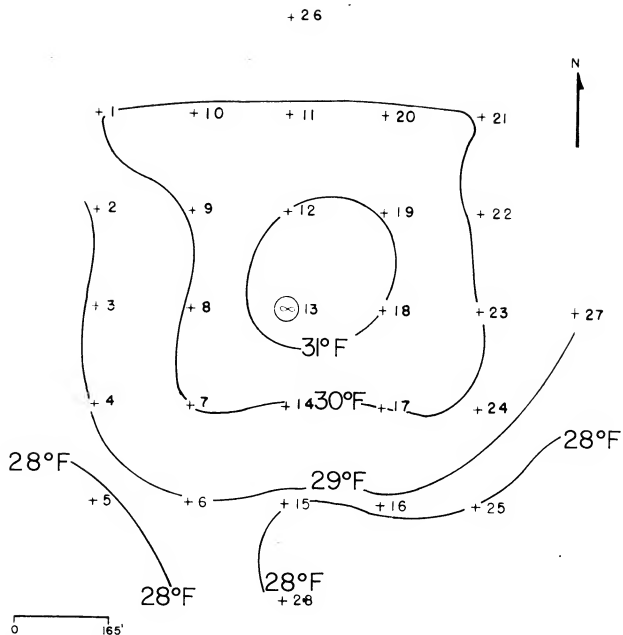
Cloud cover: Clear

Wind: Variable 0-3 mph

Maximum inversion: + 4.0°F

Check area minimum temperature: + 29.0°F

Wind machine: Operating at engine speed of
2,600 rpm



MINIMUM TEMPERATURE ISOOTHERMS
AT THE FIVE FOOT LEVEL
March 9, 1959
Fig. 13

test area were 26°F. The much lower temperatures at the south end of the test plot were attributed to the lower elevation and were not considered when determining the area receiving some protection. A very small area around the wind machine appears to have received about 1° of protection. Figure 9 shows the area receiving this small amount of protection.

Frost formed in low areas on the morning of January 24, 1959, represented by Figure 10. A very weak inversion of 2°F was recorded. One degree of protection for about four acres was provided by the wind machine.

Figure 11 shows a large area of eight to ten acres receiving 2°F protection on the morning of February 22, 1959. An inversion of 7°F was recorded. The protection pattern was deflected to the west southwest by air drift.

On March 3, 1959, an inversion of 5.0°F was recorded. Figure 12 shows the protection pattern. A large area of about eight acres came within the 2° protection pattern. Stations 8 and 9 within that area had temperatures of 30.8 and 31.0°F respectively. No valid explanation or reason for this apparent discrepancy could be determined.

Frost formed in low areas early in the morning of March 9. Figure 13 indicates a fairly small area of three to four acres as receiving 2°F protection. The inversion was 4.0°F. No frost was observed on peach foliage immediately around the wind machine but heavy frost was on dead grass throughout the area.

Wind machine operation in the 1958-59 season indicated some positive protection. The work agreed with work done in California by Brooks et al. (12) which indicated a strong correlation between inversion strength and protection obtained.

Following the 1958-59 season, mechanics made what was supposed to be a routine maintenance check on the power plant. A check of the wind machine was made and the mechanics concluded that the machine vibrated dangerously. The mechanics arbitrarily reset the governor without notifying anyone directly concerned with the project. The change in power setting was not discovered until February, 1961. A tachometer revealed that the power plant was operating at 1,800 rpm rather than the 2,600 rpm for which the machine was rated.

A discussion with members of the Mechanical Engineering staff indicated that there is a cube relationship between power plant rpm and bhp delivered at the fan. Figure 14 shows the relationship between power plant rpm and bhp delivered to the fan. At 1,800 rpm, the bhp delivered to the fan was reduced from the rated 85 bhp at 2,600 rpm down to 28.2 bhp. This reduction in bhp delivered to the fan is critical. Brooks et al. (14) reported that it takes a large (90 bhp) machine to take full advantage of strong inversions. Thrust was listed as the best single measure of a jet's effectiveness. Angus (4) found that with low-power machines the area protected varied as the cube root of power consumption.

Figures 15 through 28 show strikingly different patterns of protection from those obtained in the 1958-59 season. Even on nights

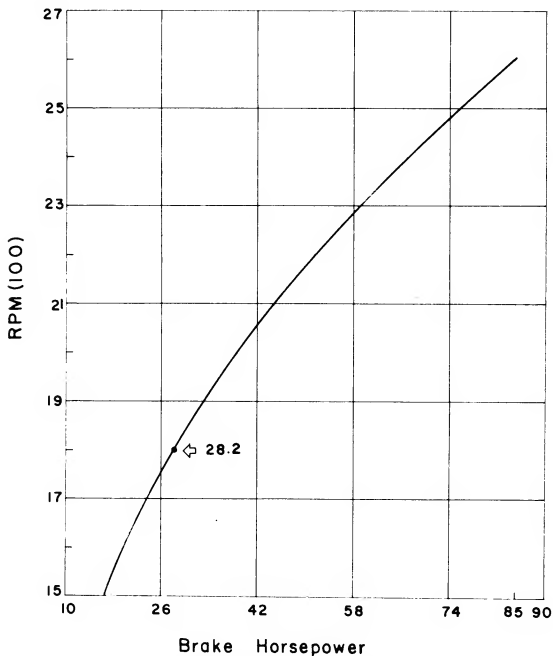


Fig. 14.-Relationship between engine rpm and bhp delivered at the fan.

Information pertinent to minimum temperature
isotherms shown in Fig. 15

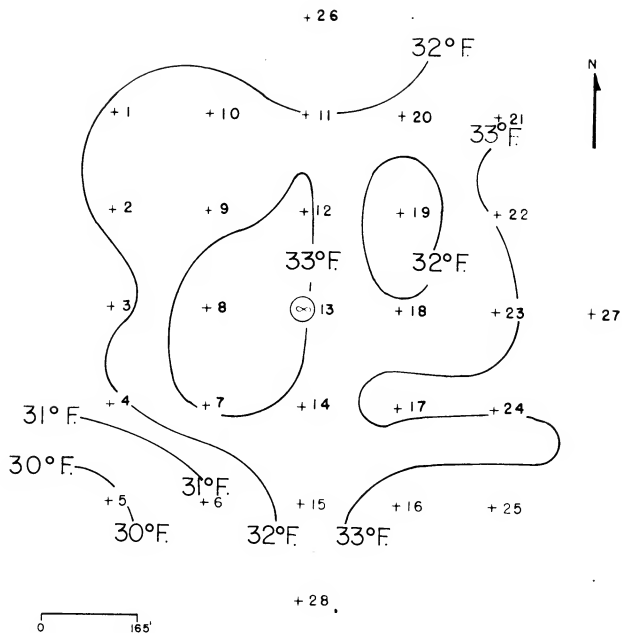
Cloud cover: Clear

Wind: Calm

Maximum inversion: + 4.2°F

Check area minimum temperature: + 32.5°F

Wind machine: Operating at engine speed of
1,800 rpm



MINIMUM TEMPERATURE ISOTHERMS
AT THE FIVE FOOT LEVEL
February 8, 1960

Fig. 15

Information pertinent to minimum temperature
isotherms shown in Fig. 16

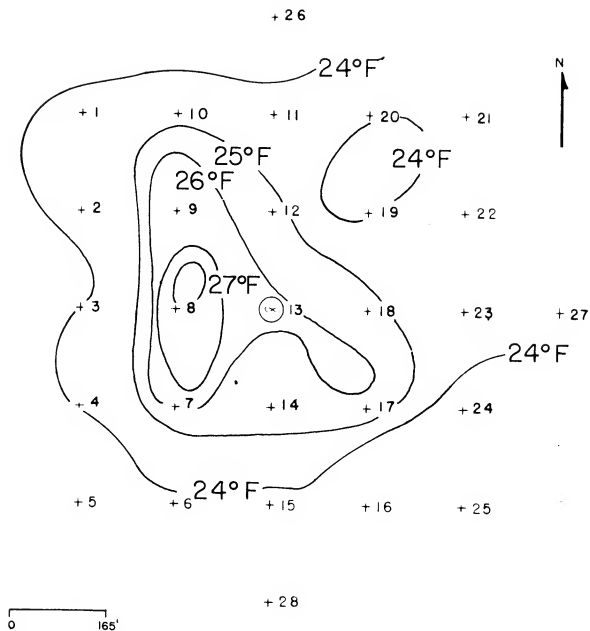
Cloud cover: Clear

Wind: Calm

Maximum inversion: + 5.0°F

Check area minimum temperature: + 24.0°F

Wind Machine: Operating at engine speed of
1,800 rpm



MINIMUM TEMPERATURE ISOTHERMS
AT THE FIVE FOOT LEVEL
February 14, 1960

Fig. 16

Information pertinent to minimum temperature
isotherms shown in Fig. 17

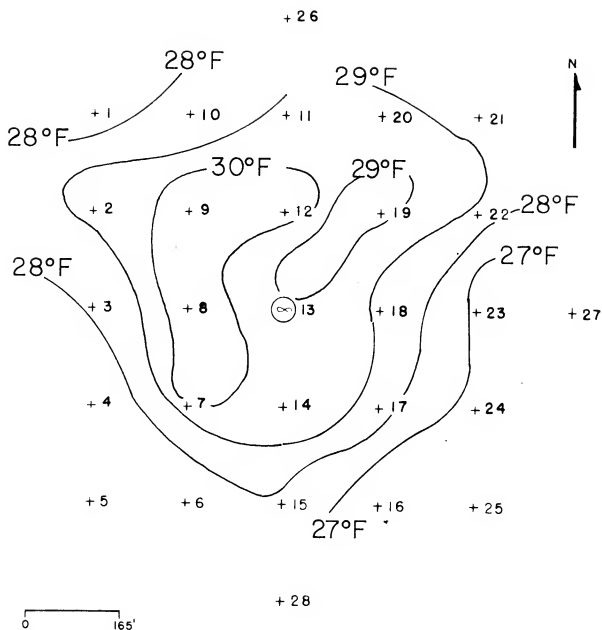
Cloud cover: Clear

Wind: Calm

Maximum inversion: + 4.0°F

Check area minimum temperature: + 28.0°F

Wind machine: Operating at engine speed of
1,800 rpm



MINIMUM TEMPERATURE ISOTHERMS
AT THE FIVE FOOT LEVEL
February 15, 1960

Fig. 17

Information pertinent to minimum temperature
isotherms shown in Fig. 18

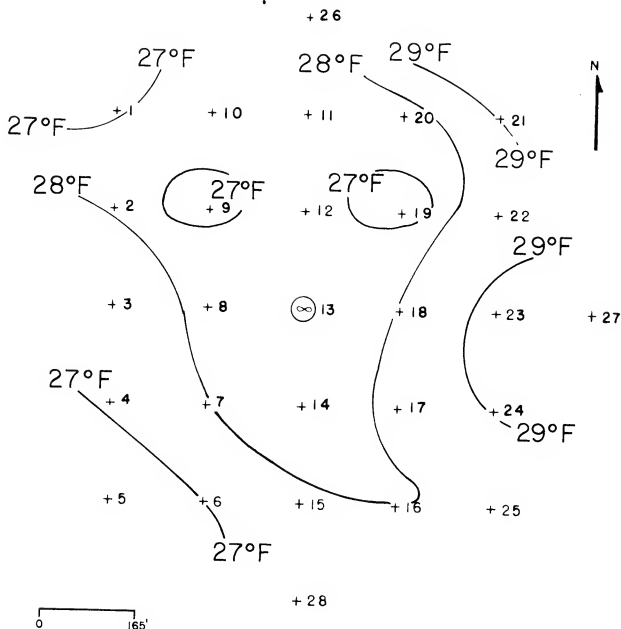
Cloud cover: Broken, drifting clouds

Wind: NW 5-7 mph

Maximum inversion: - 2.0°F

Check area minimum temperature: + 28.0°F

Wind machine: Operating at engine speed of
1,800 rpm



MINIMUM TEMPERATURE ISOTHERMS
AT THE FIVE FOOT LEVEL

February 19, 1960

Fig. 18

Information pertinent to minimum temperature
isotherms shown in Fig. 19

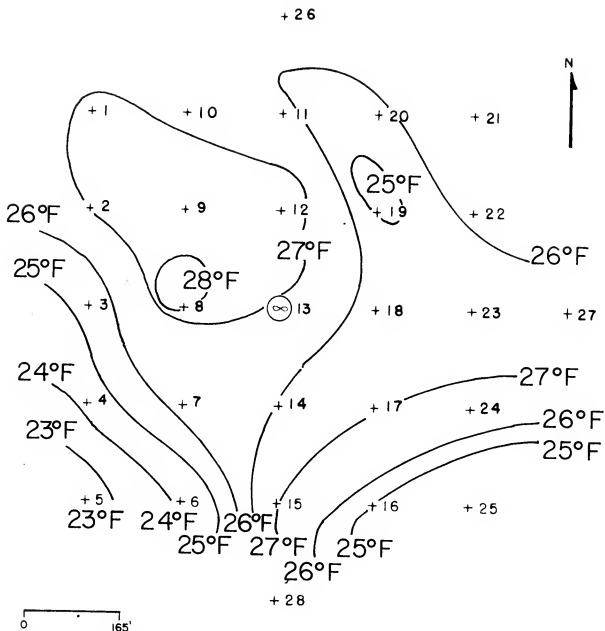
Cloud cover: Clear

Wind: WNW 0-2 mph

Maximum inversion: + 5.2°F

Check area minimum temperature: + 26.0°F

Wind machine: Operating at engine speed of
1,800 rpm



MINIMUM TEMPERATURE ISOTHERMS
AT THE FIVE FOOT LEVEL
February 20, 1960

Fig. 19

Information pertinent to minimum temperature
isotherms shown in Fig. 20

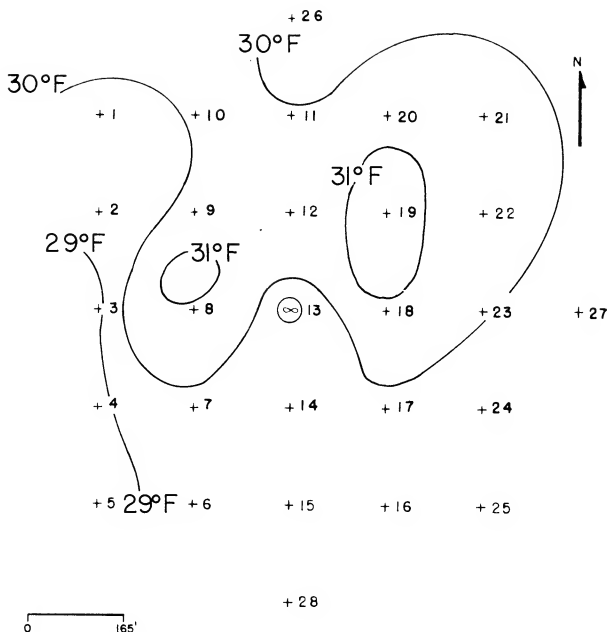
Cloud cover: Clear

Wind: Calm

Maximum inversion: + 4.0°F

Check area minimum temperature: + 30.0°F

Wind machine: Operating at engine speed of
1,800 rpm



MINIMUM TEMPERATURE ISOTHERMS
AT THE FIVE FOOT LEVEL
February 27, 1960

Fig. 20

Information pertinent to minimum temperature
isotherms shown in Fig. 21

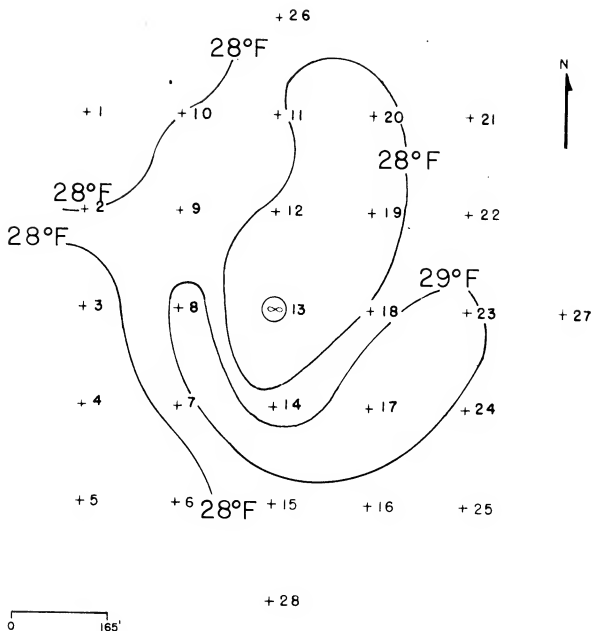
Cloud cover: Clear

Wind: NW 5-10 mph, velocity increased
at dawn

Maximum inversion: 0.0

Check area minimum temperature: + 28.0°F

Wind machine: Operating at engine speed of
1,800 rpm



MINIMUM TEMPERATURE ISOTHERMS
AT THE FIVE FOOT LEVEL
March 4, 1960

Fig. 21

Information pertinent to minimum temperature
isotherms shown in Fig. 22

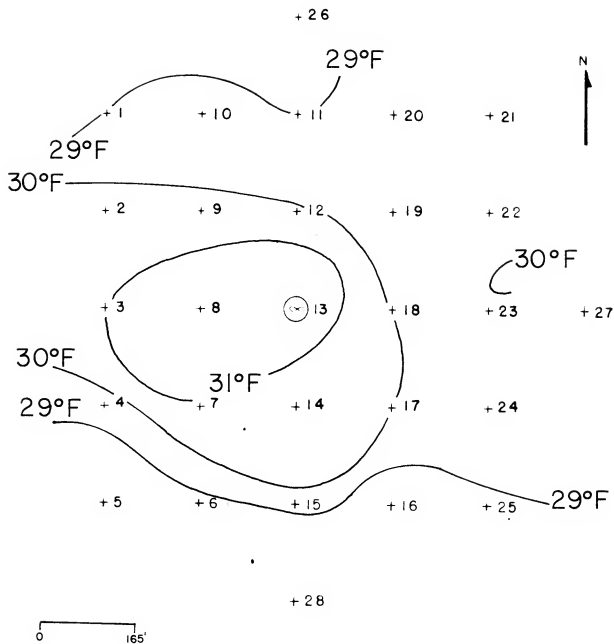
Cloud cover: Clear

Wind: N 2-4 mph

Maximum inversion: + 5.0°F

Check area minimum temperature: + 30.0°F

Wind machine: Operating at engine speed of
1,800 rpm



MINIMUM TEMPERATURE ISOTHERMS
AT THE FIVE FOOT LEVEL
March 5, 1960

Fig. 22

Information pertinent to minimum temperature
isotherms shown in Fig. 23

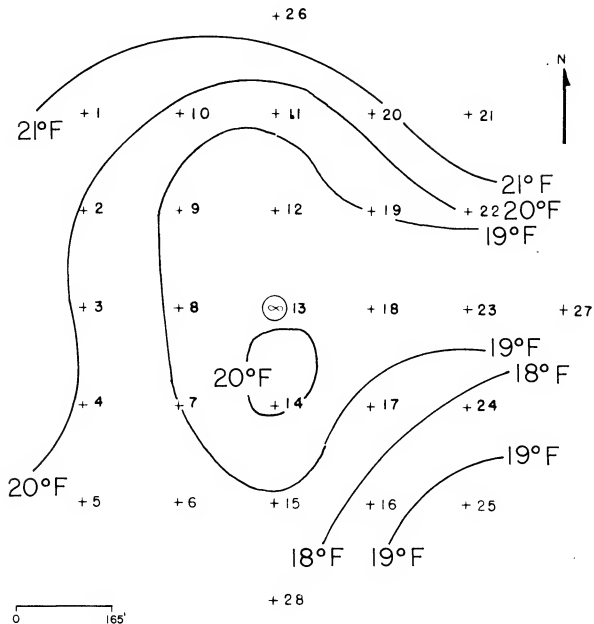
Cloud cover: Clear

Wind: Calm

Maximum inversion: + 6.5°F

Check area minimum temperature: + 21.0°F

Wind machine: Operating at engine speed of
1,800 rpm



MINIMUM TEMPERATURE ISOTHERMS
AT THE FIVE FOOT LEVEL
December 18, 1960

Fig. 23

Information pertinent to minimum temperature
isotherms shown in Fig. 24

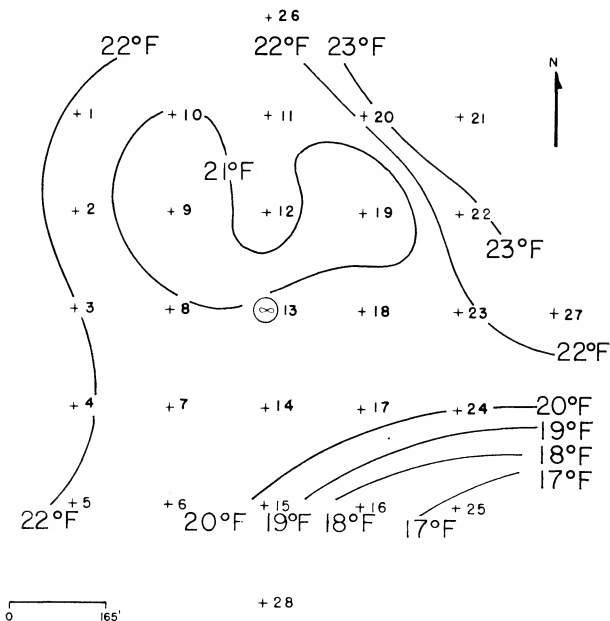
Cloud cover: Clear

Wind: W 5-7 mph

Maximum inversion: 0.0

Check area minimum temperature: + 22.5°F

Wind machine: Operating at engine speed of
1,800 rpm



MINIMUM TEMPERATURE ISOTHERMS
AT THE FIVE FOOT LEVEL
December 19, 1960

Fig. 24

Information pertinent to minimum temperature
isotherms shown in Fig. 25

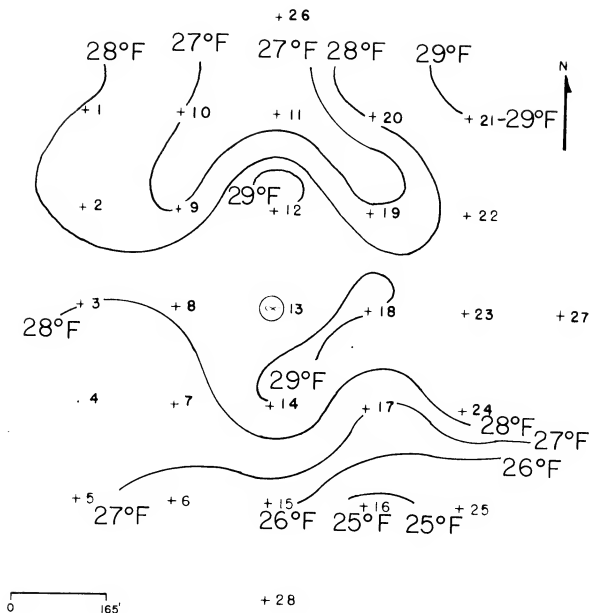
Cloud cover: Clear

Wind: Calm

Maximum inversion: + 14.1°F

Check area minimum temperature: + 28.0°F

Wind machine: Operating at engine speed of
1,800 rpm



MINIMUM TEMPERATURE ISOTHERMS
AT THE FIVE FOOT LEVEL
December 20, 1960

Fig. 25

Information pertinent to minimum temperature
isotherms shown in Fig. 26

Cloud cover: Thin, high cirrus - overcast
early in evening. Clear after 2:00 a.m.

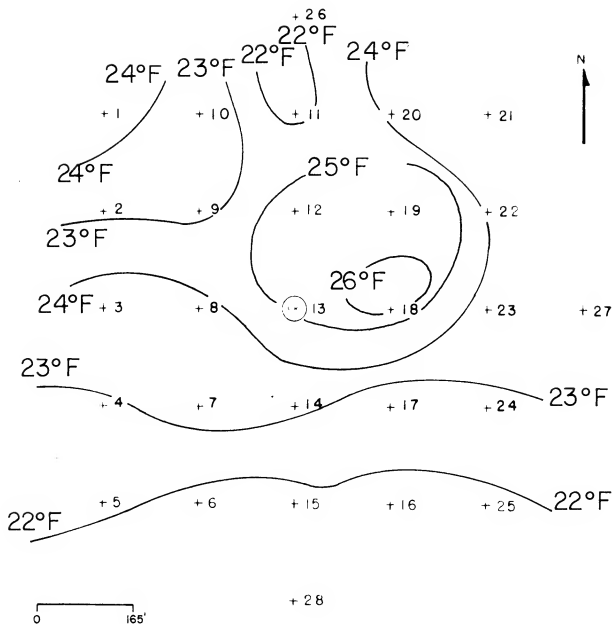
Wind: Calm

Maximum inversion: + 8.3°F

Check area minimum temperature: + 22.0°F

Wind machine: Operating at engine speed of
1,800 rpm (Started 1:10 a.m.)

Heaters: Started lighting and adjusting 10:30 p.m.



MINIMUM TEMPERATURE ISOTHERMS AT THE FIVE FOOT LEVEL

December 24, 1960

Fig. 26

Information pertinent to temperature isotherms
shown in Fig. 27

Cloud cover: Thin, high cirrus - overcast
early in evening. Clear after 2:00 a.m.

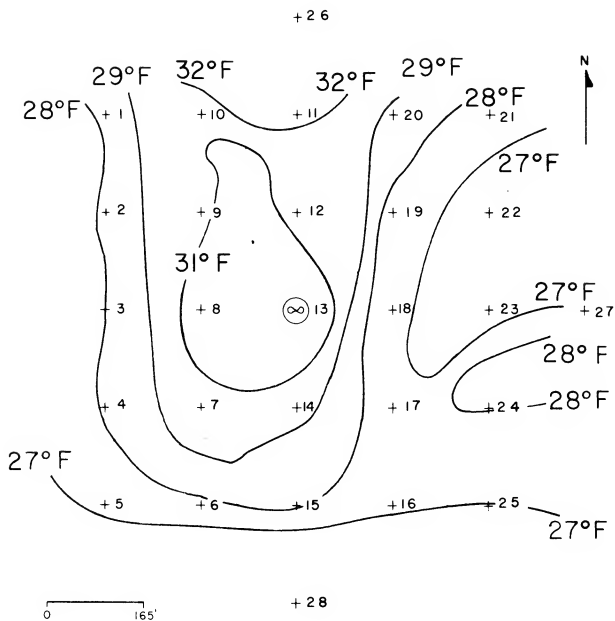
Wind: Calm

Maximum inversion: + 8.3°F

Check area minimum temperature: + 22.0°F

Wind machine: Operating at engine speed of
1,800 rpm (Started at 1:10 a.m.)

Heaters: Started lighting and adjusting
10:30 p.m.



TEMPERATURE ISOTHERMS
AT THE NINE FOOT LEVEL
December 24, 1960

Fig. 27

Information pertinent to minimum temperature
isotherms shown in Fig. 28

Cloud cover: Broken clouds until about 3:30 a.m.

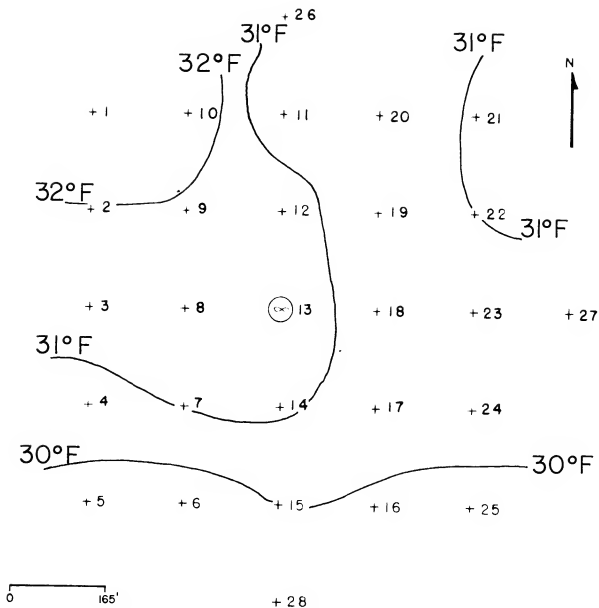
Solid cloud cover after 3:45 a.m.

Wind: Variable, NW 4-10 mph

Maximum inversion: + 3.0°F

Check area minimum temperature: + 31.0°F

Wind machine: Operating at engine speed of
1,800 rpm



MINIMUM TEMPERATURE ISOTHERMS
AT THE FIVE FOOT LEVEL
February 5, 1961

Fig. 28

of relatively strong inversions as illustrated in Figure 25, very little protection could be attributed to the wind machine. The night of February 14, 1960, illustrated in Figure 16, shows 2°F protection for about two acres with a 5°F inversion. Some protection is shown on the night of December 24, 1960 (Figure 26), but this was in combination with heaters and cannot be attributed to the wind machine alone. Heaters were lit at the rate of ten per acre within the area bounded on the north by stations 10, 11, and 20, on the south by stations 7, 14, and 16, on the east by stations 17, 18, 19, and 20, and on the west by stations 7, 8, 9, and 10. The area under heater protection was approximately five acres.

Figure 27 illustrates temperature isotherms at the 9-foot level for the same night. The temperatures were read over a time period of about five minutes by using the recording network. The network readings were taken at 3:30 a.m. and are not comparable to the 5-foot level isotherms in Figure 26. Temperatures at stations near the recorder were 2-3°F lower than the temperatures recorded at 9 feet when read five to ten minutes later. The temperature at 9 feet at the check pole at 3:15 a.m. or 15 minutes prior to the network reading was 27.8°F. This temperature was 3°F lower than the reading at 9 feet at a similar point in the test area.

Figures 28 and 29 provide information similar to that presented in Figures 26 and 27 for the night of February 5, 1961. No heater support was provided, however, and the difference in the temperatures at 9 feet at the check and test poles was only .3 of

Information pertinent to temperature isotherms
shown in Fig. 29

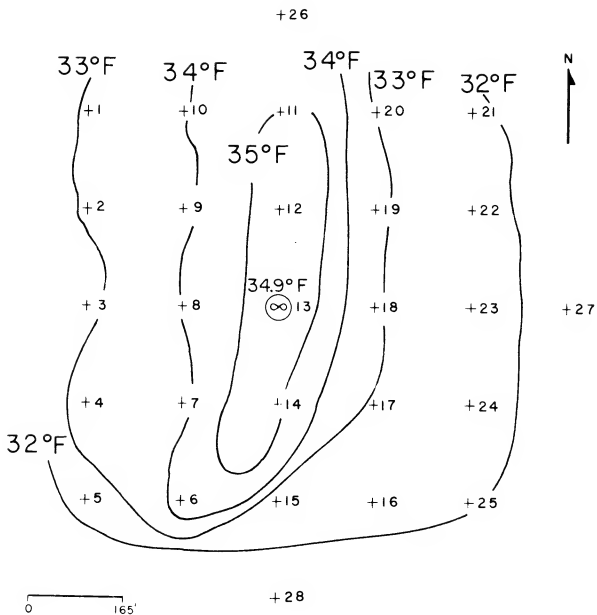
Cloud cover: Broken clouds until about
3:30 a.m. Solid cloud cover after
3:45 a.m.

Wind: Variable, NW 4-10 mph

Maximum inversion: + 3.0°F

Check area minimum temperature: + 31.0°F

Wind machine: Operating at engine speed of
1,800 rpm



TEMPERATURE ISOTHERMS
AT THE NINE FOOT LEVEL
February 5, 1961

Fig. 29

a degree. The temperature at the test pole was 33.8°F at 3:15 a.m. and 33.5°F at the check pole at 3:30 a.m.

Figures 30 and 31 represent protection patterns at 5 and 9 feet respectively and for as near the same time period as possible. The network readings were taken at 7:15 a.m. just before sunrise and were as close to the lowest temperatures for the 9-foot level as could be obtained. As a result, the isotherms for these two levels were comparable. There was about 4.5°F difference between the temperatures at 5 and 9 feet. The difference between the temperatures at 9 feet at the check and test poles was .2°F just before the network readings were taken. The large difference of 4.3°F at station 12 just north of the wind machine where the temperature recorded was 36.8°F as compared to 32.5°F on the check pole indicates positive protection from the wind machine over a relatively small area. The wind machine operating at the low engine speed did not effectively mix air in the area around the test pole located 256 feet northwest of the wind machine. The unusually high temperatures recorded on the southeast edge of the test area was because of fog that formed in the low area about 2:00 a.m. and persisted until after sunrise. Fog covered stations 16, 25, and 28.

Figures 32, 33, and 34 represent test nights after the wind machine power plant had been readjusted to give near the rated rpm. The area of 2°F or greater protection becomes fairly well defined and can be attributed to the wind machine. Figure 34 includes wind machine protection plus support from thirty-eight heaters. It is

Information pertinent to minimum temperature
isotherms shown in Fig. 30

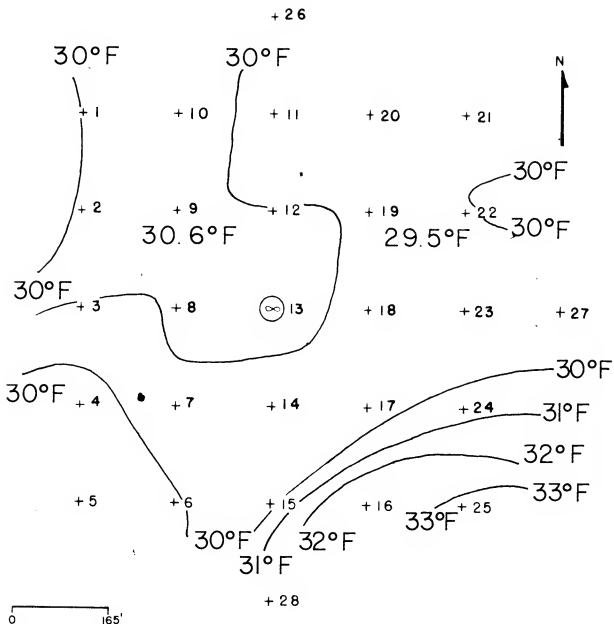
Cloud cover: Clear. Fog formed in SE quadrant
at 2:00 a.m. and persisted until after
sunrise

Wind: Calm

Maximum inversion: + 5.1°F

Check area minimum temperature: + 30.0°F

Wind machine: Operating at engine speed of
1,800 rpm



MINIMUM TEMPERATURE ISOTHERMS
AT THE FIVE FOOT LEVEL
February 11, 1961

Fig. 30

Information pertinent to temperature isotherms
shown in Fig. 31

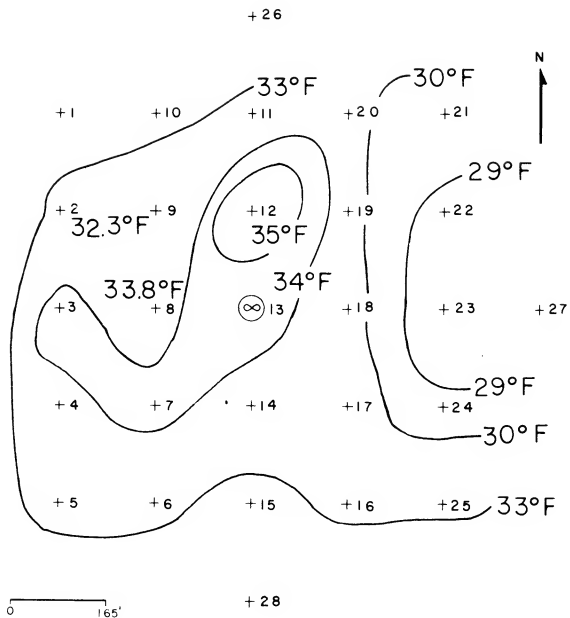
Cloud cover: Clear. Fog formed in SE
quadrant at 2:00 a.m. and persisted
until after sunrise

Wind: Calm

Maximum inversion: + 5.1°F

Check area minimum temperature: + 30.0°F

Wind machine: Operating at engine speed of
1,800 rpm



TEMPERATURE ISOTHERMS
AT THE NINE FOOT LEVEL
February 11, 1961

Fig. 31

Information pertinent to minimum temperature
isotherms shown in Fig. 32

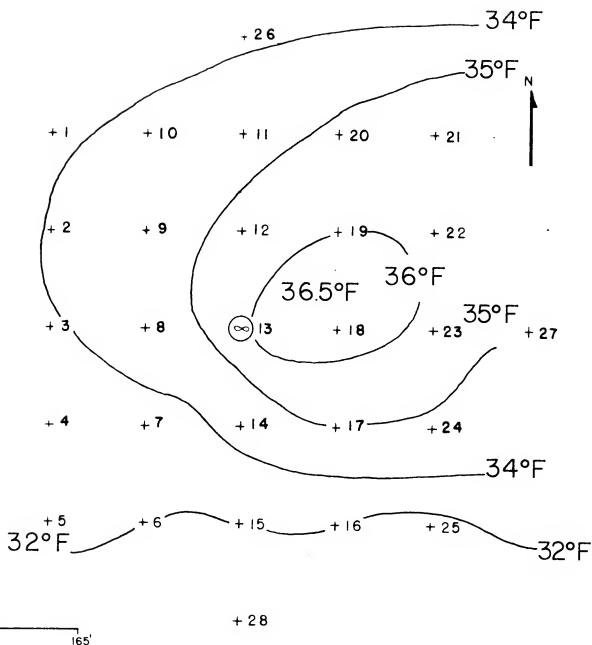
Cloud cover: Clear

Wind: W 2-4 mph

Maximum inversion: + 4.1°F

Check area minimum temperature: + 33.0°F

Wind machine: Operating at engine speed of
2,600 rpm



MINIMUM TEMPERATURE ISOTHERMS
AT THE FIVE FOOT LEVEL
February 26, 1961

Fig. 32

Information pertinent to minimum temperature
isotherms shown in Fig. 33

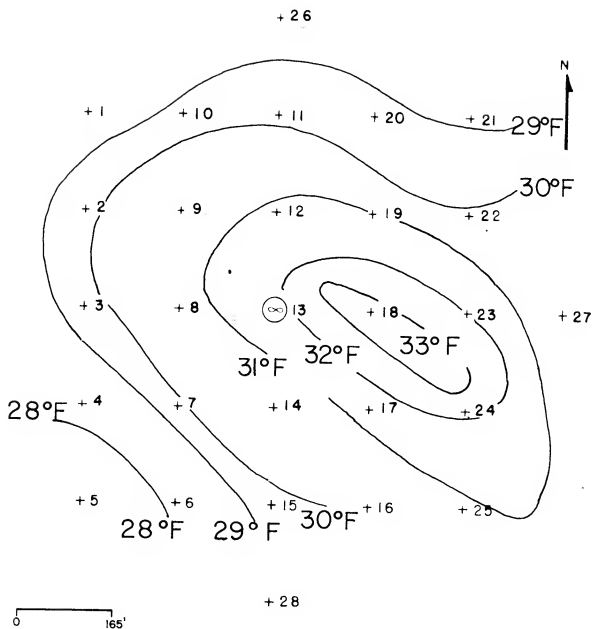
Cloud cover: Clear

Wind: W 2-4 mph

Maximum inversion: + 3.9°F

Check area minimum temperature: + 29.0°F

Wind machine: Operating at engine speed of
2,600 rpm



MINIMUM TEMPERATURE ISOTHERMS
AT THE FIVE FOOT LEVEL
March 10, 1961

Fig. 33

Information pertinent to minimum temperature
isotherms shown in Fig. 34

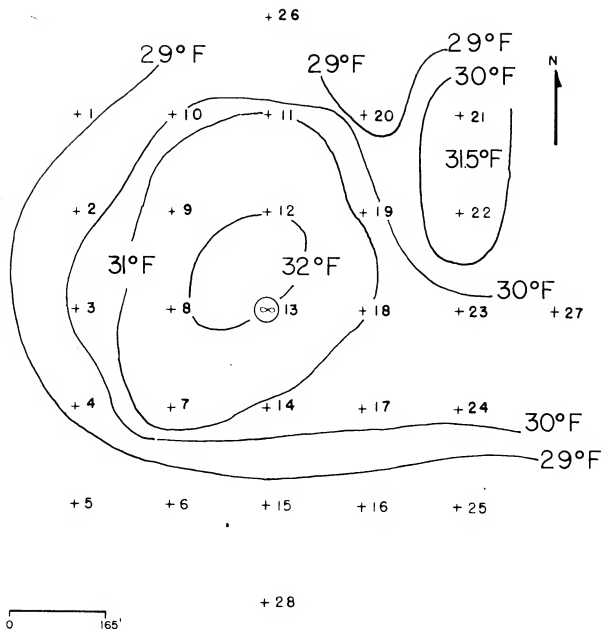
Cloud cover: Clear

Wind: Calm

Maximum inversion: + 9.9°F

Check area minimum temperature: + 28.5°F

Wind machine: Operating at engine speed of
2,600 rpm



MINIMUM TEMPERATURE ISOTHERMS
AT THE FIVE FOOT LEVEL
March 11, 1961

Fig. 34

interesting to note the displacement of protection patterns by drift on nights when the wind machine was operating efficiently as compared to the rather indeterminate patterns developed with the reduced power input.

Heaters

Some preliminary work with heaters was undertaken in the 1960-61 season. Work in California indicated desirable responses from heaters in combination with wind machines. Crawford and Leonard (22) reported on border heat in combination with wind machines for protection in deciduous orchards. Their work indicated that well distributed orchard heaters with 25 to 50 heaters per acre was the most positive means of protection. Heaters arranged in border rows 330 feet from the wind machine to form a square border around the wind machine complemented the protection offered by the wind machine.

On the night of December 24 (Figure 25), heaters were lit in a distributed pattern around the wind machine giving a total of ten heaters per acre. After the heaters were burning well they were adjusted to burn at a low level of fuel consumption. Crawford and Leonard (22) had shown that excessive heat near the wind machine tended to create bouyancy in the jet and lift it out of the orchard. After getting the heaters adjusted, the wind machine was started. The lazy-flame stack heaters used were blown out by the wind machine, if they were closer than 165 to 200 feet to the machine, unless well protected by trees. Much effort was spent in re-lighting and adjusting the heaters to get them to burn with the wind machine. It was only

with a very high rate of fuel consumption that this was accomplished. The type of heater used in this project was not satisfactory for use with the wind machine where heaters must be exposed to the direct blast of the machine.

On the night of March 11, 1961, a total of 38 heaters were lit in the ten-acre area. These were concentrated in the northeast quadrant and along the north and west borders. As temperatures dropped to a point critical for the young peaches, a few heaters were lit on a distributed pattern where they could be burned in combination with the wind machine. Heaters were burned in the northeast quadrant to protect experimental peaches that were planted in dense hedge rows. This dense planting of peach trees resisted penetration by the jet from the wind machine so effectively that heaters were not blown out. The additional response shown in the northeast quadrant of Figure 34 was undoubtedly due to heaters in the area.

Turbulence studied

Geiger (29) indicated that turbulence causes a continuous mixing of air masses. As the masses mingle so do their properties. Heat, water vapor, etc., are mixed in air many hundred times faster than heat is carried by molecular conduction or water vapor by diffusion. He further stated that in spite of certain limitations, it is predominantly eddy diffusion which is responsible for the transfer.

Elsasser (26) stated that apart from heat of condensation, all heat lost by radiation of atmosphere must be supplied to the

atmosphere by turbulent exchange and convection. He found little or no evidence of heating of the atmosphere by radiation. This work was done in absence of clouds.

Halstead and Covey (34) in giving the rate of mixing expressed as a coefficient of diffusion, proposed the mathematical model for convective heat transfer given in Chapter II. Much of the equation given will be a constant for a given set of conditions, Therefore, if expressed as:

$$q_{\text{conv}} = K(U_{2z} - U_z) (T_{2z} - T_z)$$

where,

q_{conv} = convective heat flux

K = constant

U_z = wind speed at height z

T_z = temperature at height z .

It can be seen what these workers meant when they stated that the rate of heat exchange does not depend upon wind speed, but upon the rate of change with height of the wind speed.

If this formula is viewed in relation to the wind machine and nocturnal stratification of air it can be seen that the convective heat flux will depend on the change in temperature with height and on the rate of change with height of air movement. From this it would seem that nocturnal inversions and turbulent air flow patterns created by the wind machine would be of utmost importance to mechanical mixing of air for frost protection.

Crawford and Leonard (22) observed that without natural wind to help along the air turbulence created by the wind machine, the machine would not be as effective.

Brooks et al. (15) observed that the complementary action of multiple wind machines is probably due to cross agitation of intersecting jets. This cross agitation may permit the retention of turbulence for a greater portion of wind machine turning times.

Turbulence created by the wind machine and the pattern of such turbulence was studied. Some effort had been made during the heater trials December 24, 1960, to study smoke patterns but it was difficult to make complete observations at night. In order to get some systematic observations on turbulence patterns, streamers were tied to the anchor line of a captive, helium-filled weather balloon. Observations were made beginning February 25, 1961, after the wind machine had been adjusted to the correct operating speed.

Figure 35 is designed to show the maximum depth, extent, and duration of turbulence following wind machine passage. Systematic observations were taken several nights. The balloon was anchored with 120 feet of thin nylon cable. Observations were made with the balloon anchored at each station on a north-south and east-west axis from the wind machine. Other observations were made with the balloon anchored at stations northeast of the wind machine to determine what effects, if any, the dense planting of large peaches might have on turbulence. At each station, the distance along the ground from the anchor point to a point directly beneath the balloon

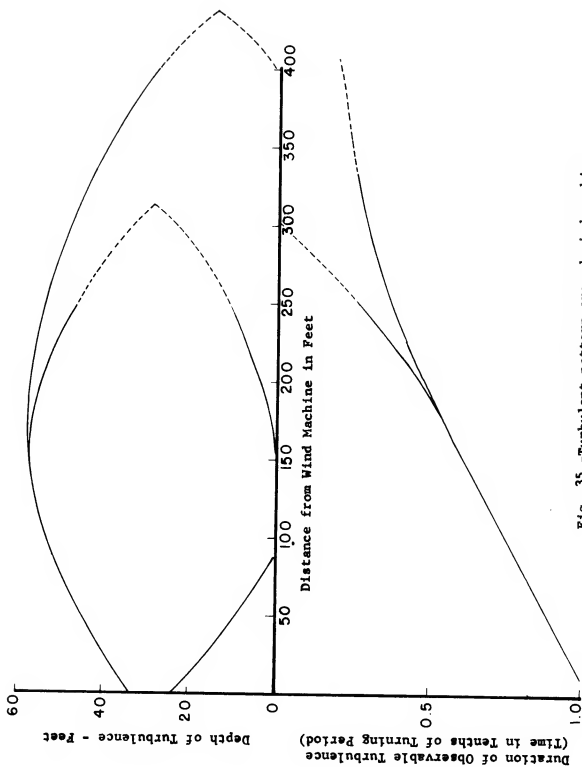


Fig. 35.-Turbulent pattern around wind machine

was measured. This made it possible to calculate a rough height on the balloon. The nylon streamers were tied to the cable at intervals of 5 feet. An estimate of the height of turbulence was obtained by counting streamers up from the ground and down from the balloon to the points showing turbulent mixing. By observing these streamers through several passages of the wind machine and by timing the turbulent movement of the streamers, it was possible to make some crude estimates of turbulence patterns actually existing in the field.

Figure 35 shows two-dimensionally the depth of turbulence in feet from the wind machine and the length of time of turbulence expressed in tenths of rotation time for the wind machine head. Penetration of turbulence is shown against the air drift and with the air drift. The dashed lines are extrapolations, but are based upon observations. The work was repeated on two subsequent nights to verify observations on depth and duration of turbulence. By assuming that convective heat transport will only occur where turbulence is effective one-fourth to one-half of the turning time and assuming no drift, the area of effective turbulent mixing should be a circle with a radius of 330 feet. This would be an area of about eight acres. Wind drift would, of course, distort the circle of protection but could increase the area of important convective transfer as implied by Crawford and Leonard (22).

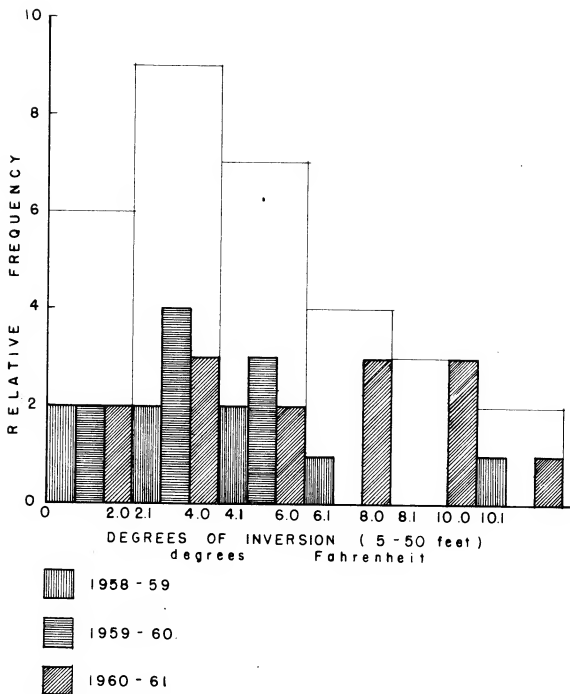
Observations made in the northeast quadrant in the dense peach planting gave two important results. First, turbulence was

violent at the intersection of the jet and the tops of the trees but very little of the turbulence penetrated the orchard to the ground level. Secondly, the orchard tops seemed to have a braking effect on the jet. The blast from the wind machine did not carry more than about 235 to 250 feet with much turbulence. Temperatures recorded in the area, however, indicated that effective heat transport did take place which could be expected under the Halstead-Covey model.

Observations of nylon streamers and of smoke around the wind machine indicated that much of the air pulled into the jet initially by the propeller comes from the air around and directly behind the propeller blade. Further entrainment of air from above comes as the jet expands. The greatest depth of turbulent mixing seemed to be in an area 75 to 200 feet from the wind machine. The apparent reduction in depth of turbulence beyond 200 feet is probably because of the turning jet beginning to break up and deviate from the law of the expanding toroid as suggested by Leonard (37). The jet actually begins to modify in form as soon as it strikes the plant cover.

Inversion strengths

The relative frequency distribution of the strength of inversions observed during the three seasons is given in Figure 36. The distribution represents mean values of inversions observed each night. The crosshatched bars represent frequencies of inversion strengths each season and the large stepped bar a summation of the three seasons. Inversions of two to six degrees account for slightly



FREQUENCY DISTRIBUTION OF INVERSIONS

Fig. 36

more than half the total observations. Weak inversions were associated in all cases with wind movement greater than two miles per hour and usually some gustiness. Strong inversions of eight or more degrees occurred when the air contained little water vapor, winds were calm, and the sky clear. Nights having strong inversions were also the nights having the coldest temperature.

It was also observed that inversions do not remain stable throughout a night. Neither do they necessarily grow stronger as the night progresses. An inversion may change during a night, weakening or strengthening depending on other factors that affect it. Sudden warming trends may develop during a night because of almost imperceptible natural mixing of air. The warming trend may prove to be transient and anyone engaged in frost protection should be aware of fluctuating inversion strengths and the effect this has on ground temperatures.

Tissue Temperatures

The ultimate objective of most frost protection work is the protection of crop plants. An understanding of the effects of frost protection methods on plant tissue is essential. This work was designed to obtain some information on the relative effects certain frost protective measures might have on ambient air and some tissue temperatures. The results may help in answering questions as to whether additional benefits accrue to plant tissue from wind machines over and above the raising of ambient air temperatures.

Brooks et al. (12) found that wind machines would raise air temperatures by 1 to 2°F over a considerable area but that the natural cooling process was not stopped. They reported that thermocouples inserted in a lemon gave readings 3.5°F colder than ambient air on the exposed side of the fruit but only 1.5°F colder on the side of the fruit adjacent to the tree.

Figure 37 indicates relative temperature differences between ambient air and the cambium area of peach and Rusk citrange tissues on a radiation night with no protection. Temperatures on which data were based were an average of four separate readings on peach and citrange. Temperatures were recorded from about midnight until 5:00 a.m. A possible explanation for the differences in tissue temperatures between peach and citrange is that the peach was bare of foliage and the bark was exposed to the sky whereas the citrange had leaves above the point of temperature measurement. These leaves may have reduced net radiation losses from the tissue of the citrange. Another possible reason was that all of the citranges were small and the thermocouples were inserted in the tissue of the trunks about four to five inches above bare soil. The soil may have supplied heat to the citrange.

Figure 38 shows relative tissue temperature differences taken in the same plants on the night of February 11, 1961. The relative difference between peach and citrange tissue was about the same as on the previous night but the spread between the two and ambient air was greater. Dew started forming about 3:00 a.m. and the tissue

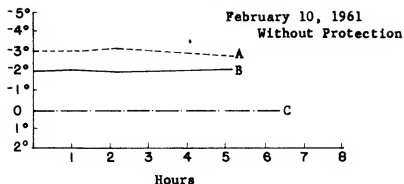


Fig. 37.-Relative temperature differences between ambient air and cambium and contiguous tissues of peach and Rusk citrange

- A - Peach cambium and contiguous area - no foliage
- B - Rusk citrange cambium and contiguous area
- C - Ambient air

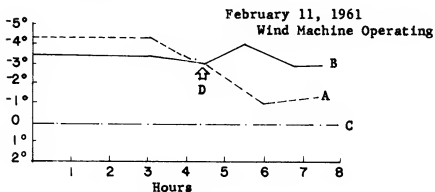


Fig. 38.-Relative temperature differences between ambient air and cambium and contiguous tissues of peach and Rusk citrange

- A - Peach cambium and contiguous area - no foliage
- B - Rusk citrange cambium and contiguous area
- C - Ambient air
- D - Wind machine on

temperature of both peach and citrange moved closer to ambient air temperature until 4:30 a.m. At this time the tissues were reading together and the ambient air was at 34.0°F. The wind machine was turned on and the dew on the exposed peach branches started to freeze. The dew on the low citrange plants did not freeze. The peach tissue continued to approach the ambient air temperature until all dew was frozen and then gradually temperature differences started to widen.

Figures 39 and 40 show results of measurements taken March 10, 1961, with the wind machine used for protection. This was after the wind machine had been adjusted to the desired power input. Figure 39 shows the tissue temperatures with foliage on the peach from midnight to 6:30 a.m. The peach and citrange tissue temperatures were now essentially the same. Figure 39 shows the average tissue temperatures for both peach and citrange for thirty minutes before turning on the wind machine and for ninety minutes thereafter. There was a very slow reduction in the difference between the tissue temperatures and ambient air for the ninety minutes. Figure 40 at 3:30 a.m. represents readings from that point on and shows the spread between tissue and ambient air temperatures to remain about the same for the rest of the night.

On March 11, 1961, temperatures dropped below freezing and remained there for several hours. A thermograph outside the protected area showed 28.5°F for one and one-half hours. The wind machine was used for protection with a few supporting heaters. One

Fig. 39.-Relative temperature differences
between ambient air and cambium and contiguous
tissues of peach and Rusk citrange

- A - Average cambium and contiguous area temperature
differences for peach and Rusk citrange
- B - Ambient air
- C - Wind machine on

Fig. 40.-Relative temperature differences
between ambient air and cambium and contiguous
tissues of peach and Rusk citrange

- A - Peach leafed out
- B - Rusk citrange
- C - Ambient air
- D - Wind machine on

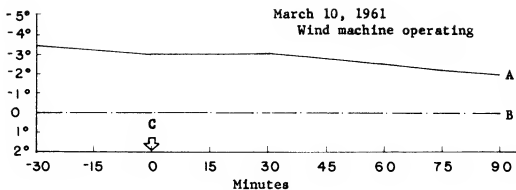


Fig. 39

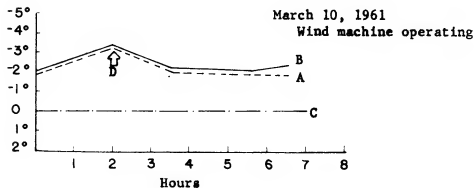


Fig. 40

of the heaters was lit at 5:00 a.m. within 5 feet of the peach tree that had thermocouples inserted under the bark. One thermocouple was positioned in tissue directly exposed to radiant heat from the heater. Figure 41 shows the rapid warming of peach tissue as a result of the radiant heat. The citrange was about 20 feet from the heater and was not affected. Figure 42 shows the citrange and peach tissue measured at a point on the tree directly away from the heater. This tissue remained relatively unaffected by the radiant heat.

Figures 43 and 44 compare average tissue temperatures with ambient air and show the actual temperatures at which the measurements were taken. Figure 43 is an average of 19 leaf temperatures. Attention is called to the relatively short period of time required for leaves to reach an equilibrium with ambient air as compared to the under bark temperature adjustment.

Figure 45 shows the relative temperature differences between ambient air and peach leaves before and after starting the wind machine. These measurements were taken between 4:00 a.m. and 6:00 a.m. with temperatures in the fifties.

An effort was made to duplicate some of the above results with leaf temperatures under controlled conditions. Small peach trees were placed in an insulated box inside a dark cold room. The peach leaves had thermocouples inserted at several levels within the box.

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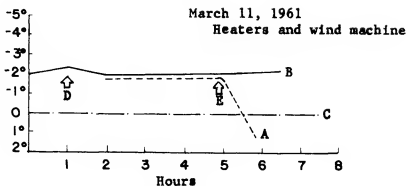


Fig. 41.-Relative temperature differences between ambient air and cambium and contiguous tissues of peach and Rusk citrange

- A - Peach leafed out - exposed to heater at a distance of 5 feet
- B - Rusk citrange
- C - Ambient air
- D - Wind machine on
- E - Heater lit

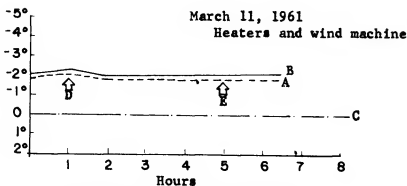


Fig. 42.-Relative temperature differences between ambient air and cambium and contiguous tissues of peach and Rusk citrange

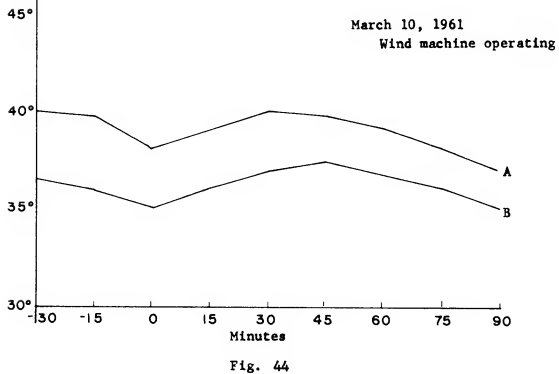
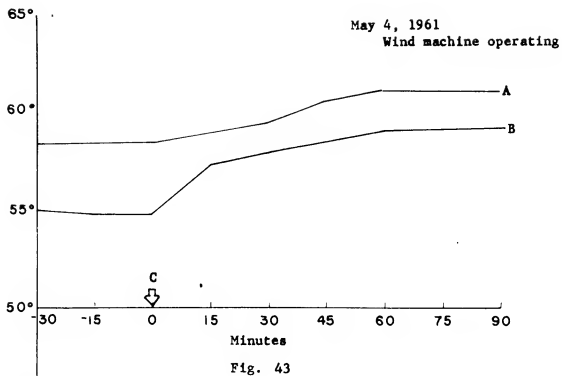
- A - Peach leafed out - temperature measured on opposite side of tree from heater
- B - Rusk citrange
- C - Ambient air
- D - Wind machine on
- E - Heater lit

Fig. 43.-Comparison of ambient air temperature
with average peach leaf temperatures

- A - Ambient air temperature at 5'
- B - Average peach leaf temperatures
- C - Wind machine on

Fig. 44.-Comparison of ambient air temperature
with average cambium and contiguous tissue temperatures

- A - Ambient air temperature at 5'
- B - Average tissue temperatures



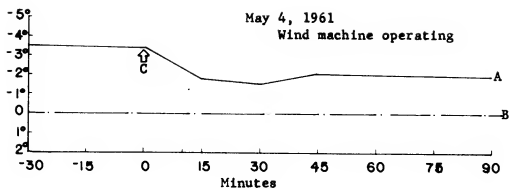


Fig. 45.-Relative temperature differences between ambient air and peach leaves

- A - Average peach leaf temperature differences
- B - Ambient air
- C - Wind machine on

A polyethylene cover was placed over the top of the box to try and simulate radiation effects. Temperatures were measured with the Brown recorder for a period of about three days without getting positive results. There was evidently some stratification of air in the box as evidenced by the two lower leaves being about a half degree colder than the leaves near the top of the box but the ambient air temperature in the box was exactly the same as leaf temperatures at the same height.

These results indicate that tissue temperatures do cool several degrees below ambient air temperatures on radiation nights. Wind machines used for protection do not warm tissue temperatures above ambient air temperatures but the spread between tissue temperatures and ambient air temperature is narrowed. If there are benefits from wind machines not associated with this warming of ambient air and plant tissue temperatures, they were not apparent from the research results obtained. Supercooling of plant tissues without freezing has often been pointed up as being a reason plants can stand lower temperatures than would be expected. Instrumentation and methods used did not give data that would indicate wind machine effects on supercooled plant tissue or on what part evaporative cooling may play in reducing protection afforded by wind machines. The results in the cold chamber would certainly indicate that research workers relying entirely on climate chambers should use caution in making recommendations dealing with critical plant temperatures when

these recommendations are to be applied to the field. Certainly considerations must be given to the lowering of plant tissue temperatures below that of ambient air in recommendations on frost protection.

V. CONCLUSIONS

Risks resulting from frost hazards can be reduced by wind machines. Protection amounting to about 2°F was obtained over an area of five to ten acres as indicated on isotherm charts prepared for the test area. The protection obtained depended on power input and existing weather conditions.

Wind machine operation seems to raise plant tissue temperatures along with raising the temperature of ambient air. This research indicates that temperature differences between plant tissue and ambient air narrows when under wind machine protection but tissue temperatures never become warmer than ambient air from wind machine operation alone. Leaf temperatures reach an equilibrium with ambient air much more rapidly than tissues of the cambium and contiguous areas. An external heat source supplying direct radiant heat to plant tissue can raise tissue temperatures above ambient air temperatures.

The results of limited work in a climate chamber indicate that field conditions are difficult to simulate. Results from climate chambers should be field tested before being released as recommendations. Plant tissues in this work cooled from 2-4°F below ambient air temperature. Such a possibility should be pointed out to growers who depend on measured grove or orchard air temperatures. Further work should probably be done in this area.

Preliminary work on turbulent air flow created by a wind machine was admittedly crude but the extent and duration of turbulence indicated a protected area of about 330 feet from the wind machine when not affected by air drift. A circle with a radius of 330 feet would encompass about eight acres in which 2°F protection could be expected with inversions of 6°F. Further work needs to be done in this area, particularly on the relationships of turbulent air flow and heat transport within citrus groves with dense foliage. Much more sensitive instrumentation will be required to obtain the basic information needed than is presently available to the project. Measurement of air movement at several levels would seem to be essential as well as measurement of vertical heat transport. Better instrumentation will be needed to do this.

The outer limits of effective turbulence seemed to be at about the point where turbulent mixing was observed to be less than one-fourth to one-half of the rotating time of the wind machine head. Spacing of wind machines to allow some interaction of jets in this area should reduce the periods of calm and increase the area of effective turbulent mixing of overhead warm air and cold air near the surface. Brooks et al. (14) indicated that four machines complemented each other and gave wider protection than the sum of areas protected by four single machines.

The effective area of protection found in the deciduous orchard, primarily peach, was less than reported for citrus in

California and Florida. Additional research is needed with wind machines in Florida citrus groves.

Temperature inversions occurred on all clear, calm nights. Inversion strength varies from night to night and within the same night depending on conditions.

This research work indicated rpm of the power plant to be a critical factor in wind machine operational efficiency. Growers need to be informed of this critical factor and it is recommended that a tachometer be included in the machine instrument panel so that rpm of the power plant can be easily checked.

Additional work is needed in Florida with wind machines in combination with heaters to further reduce frost hazards in cold locations. A type of heater needs to be used that can be operated with low heat output when distributed in an area under wind machine protection.

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APPENDIX

TABLE 5
CORRECTED MINIMUM TEMPERATURES IN
DEGREES FAHRENHEIT BY STATIONS

Station	<u>1/6/59</u>		<u>1/11/59</u>		<u>1/13/59</u>	
	1' Level	5' Level	1' Level	5' Level	1' Level	5' Level
1	29.5	30.0	20.2	20.0	-	27.5
2	29.0	30.0	20.0	20.3	27.8	28.0
3	30.0	30.2	20.0	20.2	28.5	28.8
4	29.0	30.0	19.0	18.9	27.5	27.8
5	27.5	29.0	17.2	18.0	26.0	27.0
6	30.1	30.0	18.5	19.0	26.5	27.0
7	30.5	31.1	21.8	22.0	28.5	29.2
8	31.0	31.8	22.0	22.1	29.2	30.0
9	32.0	32.0	22.0	22.0	28.0	28.5
10	30.0	30.5	20.5	21.0	27.5	-
11	32.0	32.0	21.0	21.2	28.0	28.1
12	33.0	33.1	22.0	22.1	29.5	29.8
13	33.0	33.5	22.0	22.5	32.0	32.2
14	32.0	32.1	22.0	22.3	30.0	30.1
15	30.0	30.2	20.0	20.5	26.5	26.8
16	29.1	30.0	20.0	20.5	26.5	27.0
17	32.0	32.0	22.0	22.0	29.5	30.0
18	33.1	33.3	22.5	22.5	32.0	32.2
19	33.0	33.2	21.5	22.0	29.5	29.8
20	30.5	31.0	20.0	20.9	27.5	28.0
21	29.0	30.0	19.5	20.0	27.0	-
22	30.8	31.4	20.0	20.9	28.0	28.2
23	31.5	32.0	21.3	22.0	29.5	30.0
24	30.0	30.8	20.8	21.2	28.5	29.0
25	29.0	29.5	20.0	20.0	27.0	27.2
26	29.3	30.0	19.8	20.0	-	26.8
27	29.5	30.0	20.0	20.1	-	28.0
28	27.5	29.0	17.5	18.0	-	25.8

TABLE 6
CORRECTED MINIMUM TEMPERATURES IN
DEGREES FAHRENHEIT BY STATIONS

Station	<u>1/17/59</u>		<u>1/24/59</u>		<u>2/22/59</u>	
	1' Level	5' Level	1' Level	5' Level	1' Level	5' Level
1	26.0	26.0	32.5	32.8	31.0	31.0
2	25.5	26.0	33.0	33.2	31.8	32.0
3	25.5	25.0	-	33.2	-	32.1
4	21.5	22.0	33.0	33.0	32.0	32.0
5	18.3	18.8	30.5	30.8	27.5	28.0
6	19.0	19.3	31.5	31.8	30.5	31.0
7	26.0	26.0	33.0	33.5	32.8	33.0
8	27.0	27.2	33.5	34.0	33.5	34.1
9	26.5	26.8	33.5	33.8	32.5	32.8
10	26.0	26.5	33.0	33.5	30.5	30.8
11	26.0	26.5	33.0	33.5	30.0	30.2
12	26.5	26.7	33.5	34.1	33.0	33.0
13	27.0	27.5	34.0	34.5	34.0	34.5
14	27.0	27.2	34.0	34.0	33.0	33.0
15	23.0	23.2	33.0	33.0	31.0	31.0
16	24.5	24.9	33.0	-	28.0	28.0
17	26.0	26.5	34.0	34.1	31.5	32.0
18	26.0	26.8	34.0	34.5	31.5	32.0
19	26.0	26.5	34.0	34.0	31.5	31.0
20	26.0	26.5	33.0	33.5	30.0	30.2
21	25.2	26.0	33.0	33.0	30.0	30.0
22	26.0	26.2	33.0	33.5	30.0	30.5
23	26.0	26.2	34.0	34.1	30.0	30.5
24	25.5	26.0	34.0	34.0	30.0	30.2
25	22.0	22.8	31.5	32.0	27.6	28.0
26	25.5	26.0	32.5	33.0	28.5	29.0
27	24.5	24.8	32.8	33.0	29.5	30.0
28	17.0	17.5	30.5	30.9	27.5	28.0

TABLE 7
CORRECTED MINIMUM TEMPERATURES IN
DEGREES FAHRENHEIT BY STATIONS

Station	<u>3/3/59</u>		<u>3/9/59</u>		<u>2/8/60</u>	
	1' Level	5' Level	1' Level	5' Level	1' Level	5' Level
1	32.0	33.0	29.8	30.0	-	32.0
2	32.5	33.0	29.0	29.0	31.3	32.8
3	32.0	32.0	29.0	-	31.0	31.5
4	31.0	31.5	28.5	29.0	32.0	32.0
5	29.0	29.5	27.0	27.0	-	30.1
6	30.0	31.0	28.5	29.0	32.0	31.2
7	31.6	32.0	29.6	30.0	33.0	33.5
8	30.5	30.8	29.8	30.0	33.0	33.1
9	31.0	31.0	29.8	30.0	32.0	32.5
10	32.3	33.0	29.5	30.0	32.0	32.1
11	32.7	33.1	29.5	30.0	32.1	31.5
12	33.5	34.0	32.0	32.0	32.5	33.0
13	34.0	34.5	32.0	32.4	32.5	33.0
14	30.8	31.0	30.0	29.8	33.0	33.0
15	30.2	30.5	27.0	27.5	32.0	32.5
16	29.0	29.5	28.5	29.0	31.0	32.0
17	30.5	31.0	30.0	30.0	33.0	33.0
18	33.0	33.0	32.0	32.0	32.1	32.0
19	33.0	34.0	32.0	32.0	32.0	31.5
20	32.2	33.0	30.0	30.2	31.6	32.0
21	31.0	32.0	29.0	30.0	-	32.5
22	31.5	32.1	29.0	29.5	32.5	33.0
23	31.5	-	29.2	30.0	32.2	33.0
24	31.2	32.0	29.0	30.0	32.6	33.0
25	30.0	30.4	27.0	27.5	-	31.2
26	29.5	31.0	28.5	29.0	-	31.5
27	29.5	31.0	28.8	29.0	-	31.0
28	29.0	29.5	27.0	27.5	-	30.5

TABLE 8
CORRECTED MINIMUM TEMPERATURES IN
DEGREES FAHRENHEIT BY STATIONS

Station	<u>2/14/60</u>		<u>2/15/60</u>		<u>2/19/60</u>	
	1' Level	5' Level	1' Level	5' Level	1' Level	5' Level
1	-	24.0	-	27.5	-	27.0
2	22.8	24.8	26.8	29.3	26.8	28.0
3	23.5	23.5	28.0	28.0	27.5	27.0
4	24.0	24.5	27.5	27.5	27.5	27.5
5	-	22.6	-	25.6	-	24.1
6	25.0	24.2	28.0	27.7	27.0	27.2
7	26.0	27.0	28.5	30.0	27.0	28.0
8	26.5	28.1	29.5	30.1	27.0	29.1
9	25.5	25.5	30.0	30.0	27.0	27.0
10	24.0	24.1	28.5	28.6	27.0	27.6
11	24.1	24.0	28.1	29.0	26.1	27.5
12	25.0	25.0	30.0	30.0	27.5	27.5
13	26.0	26.0	29.5	29.0	28.0	28.0
14	25.5	25.5	30.0	29.5	27.0	27.5
15	24.0	24.5	28.0	28.0	27.0	28.0
16	22.0	23.0	27.0	27.5	27.0	28.0
17	26.0	26.0	29.5	29.5	29.5	29.5
18	25.1	25.0	29.6	29.0	28.6	28.0
19	25.0	23.5	29.0	28.0	27.5	27.0
20	24.1	24.5	29.1	29.0	27.1	28.0
21	-	25.0	-	30.0	-	29.0
22	25.0	24.5	28.0	29.0	27.5	28.5
23	24.2	24.5	27.2	27.0	28.2	29.0
24	24.1	24.0	27.1	27.0	28.6	29.0
25	-	22.7	-	26.2	-	28.2
26	-	23.5	-	27.0	-	28.0
27	-	23.0	-	26.0	-	28.0
28	-	22.0	-	25.5	-	27.0

TABLE 9
CORRECTED MINIMUM TEMPERATURES IN
DEGREES FAHRENHEIT BY STATIONS

Station	<u>2/20/60</u>		<u>2/27/60</u>		<u>3/4/60</u>	
	1' Level	5' Level	1' Level	5' Level	1' Level	5' Level
1	-	27.0	-	30.0	-	28.5
2	25.3	-	29.3	29.8	27.8	28.8
3	25.0	25.0	29.0	29.0	27.0	27.0
4	25.0	24.5	29.0	29.0	28.0	27.5
5	-	22.6	-	28.1	-	27.1
6	24.5	24.2	30.0	29.2	28.5	28.7
7	25.0	26.5	29.5	30.0	27.5	29.0
8	26.5	28.1	29.5	31.1	28.0	29.1
9	27.0	27.5	29.5	30.0	28.0	27.5
10	26.0	26.6	29.0	30.1	28.0	28.1
11	23.1	26.0	29.1	29.5	28.1	28.0
12	27.0	27.0	30.0	30.0	28.0	28.0
13	27.0	27.0	30.0	30.0	29.0	28.5
14	26.0	26.0	30.0	29.0	29.0	28.0
15	26.0	27.0	29.5	29.5	28.5	29.0
16	25.0	26.0	28.0	29.5	28.0	29.0
17	27.0	27.0	30.5	30.0	30.0	29.5
18	26.6	26.0	30.1	29.0	28.6	28.0
19	25.0	25.0	30.0	29.0	28.5	-
20	25.1	26.0	29.6	30.0	27.1	28.0
21	-	27.0	-	30.0	-	28.5
22	26.0	25.5	30.0	30.0	28.0	28.5
23	25.7	26.5	30.7	30.5	28.2	29.0
24	25.6	27.0	29.6	29.5	28.6	29.0
25	-	23.5	-	29.2	-	28.7
26	-	-	-	28.5	-	28.5
27	-	-	-	29.0	-	27.0
28	-	24.5	-	28.5	-	27.5

TABLE 10
CORRECTED MINIMUM TEMPERATURES IN
DEGREES FAHRENHEIT BY STATIONS

Station	<u>3/5/60</u>		<u>12/18/60</u>		<u>12/19/60</u>	
	1' Level	5' Level	1' Level	5' Level	1' Level	5' Level
1	-	29.0	18.5	21.0	21.5	22.0
2	30.8	31.8	18.1	20.5	21.1	21.5
3	30.0	31.0	20.0	20.0	22.0	22.0
4	28.0	30.0	19.0	-	21.0	-
5	-	25.1	19.1	19.2	21.5	22.2
6	29.0	29.0	18.5	18.5	21.0	20.5
7	30.5	31.0	-	18.8	22.5	21.8
8	30.0	31.1	19.8	19.0	20.8	21.0
9	30.0	30.0	19.0	19.0	20.5	20.5
10	29.0	29.6	19.0	20.1	21.0	21.1
11	29.1	29.0	18.0	17.1	20.0	21.5
12	29.0	29.5	19.1	19.5	21.1	21.5
13	31.0	31.5	19.0	19.6	21.0	21.1
14	30.0	30.5	19.0	20.0	21.0	21.5
15	29.5	30.0	18.1	19.0	21.1	21.0
16	28.0	28.5	15.0	18.0	18.0	19.0
17	30.0	30.0	16.0	18.5	20.0	21.5
18	29.6	29.0	18.0	19.5	20.0	21.5
19	29.0	29.5	17.0	18.0	21.0	20.5
20	29.1	29.5	18.0	21.0	20.0	23.0
21	-	29.5	21.0	21.1	22.5	23.1
22	29.0	29.5	21.0	21.0	23.0	23.0
23	29.7	30.0	19.0	20.1	22.0	22.1
24	29.6	29.5	18.0	18.0	21.5	22.0
25	-	29.2	19.0	19.5	18.0	18.0
26	-	28.0	21.2	21.5	23.2	23.5
27	-	28.0	20.2	20.0	22.7	22.5
28	-	27.0	17.0	17.0	18.0	19.5

TABLE 11

CORRECTED MINIMUM TEMPERATURES IN
DEGREES FAHRENHEIT BY STATIONS

Station	<u>12/20/60</u>		<u>12/24/60</u>		<u>2/5/61</u>	
	1' Level	5' Level	1' Level	5' Level	1' Level	5' Level
1	27.5	28.0	23.0	24.0	32.6	32.0
2	27.1	27.5	-	23.5	31.0	32.0
3	28.0	28.0	24.0	24.0	30.6	31.9
4	27.0	-	22.0	-	29.0	30.4
5	26.1	27.2	22.5	22.7	29.5	29.7
6	27.0	26.5	22.5	21.5	30.5	29.5
7	28.5	27.8	24.0	23.8	31.0	31.2
8	28.8	28.0	24.3	24.0	30.0	31.5
9	27.0	27.0	23.0	23.5	29.9	32.0
10	26.0	27.1	23.5	23.6	30.0	32.1
11	27.0	26.5	23.0	22.0	29.3	30.5
12	27.1	29.0	23.1	25.5	28.5	31.0
13	28.5	28.1	25.0	25.1	29.0	-
14	28.0	29.0	23.0	24.0	30.1	31.2
15	26.1	27.0	22.1	22.0	28.0	30.3
16	24.0	25.0	19.0	21.0	26.0	29.6
17	26.5	27.5	21.0	22.5	28.1	30.5
18	28.0	29.0	24.5	26.0	29.0	30.5
19	27.0	27.0	24.0	23.5	29.5	30.4
20	25.0	28.5	25.5	24.0	28.5	30.5
21	28.0	29.1	24.0	24.1	31.2	31.1
22	28.0	28.5	24.0	24.0	28.0	31.0
23	27.5	28.1	23.0	23.6	28.6	30.5
24	27.5	28.5	23.5	23.0	30.5	31.0
25	25.0	25.5	21.0	22.0	27.0	29.0
26	28.2	28.0	25.2	24.0	31.5	32.8
27	28.2	27.0	25.2	24.0	29.3	32.5
28	23.0	25.0	18.5	20.5	27.0	30.0

TABLE 12
CORRECTED MINIMUM TEMPERATURES IN
DEGREES FAHRENHEIT BY STATIONS

Station	<u>2/11/61</u>		<u>2/26/61</u>		<u>3/10/61</u>	
	1' Level	5' Level	1' Level	5' Level	1' Level	5' Level
1	30.8	30.0	34.3	34.0	30.3	31.0
2	29.0	30.0	33.0	34.0	29.5	30.0
3	28.6	30.1	33.1	34.1	29.1	30.1
4	28.0	28.9	32.0	32.4	27.0	28.4
5	29.0	29.2	31.5	32.2	26.5	27.7
6	30.0	29.0	32.5	32.0	28.0	28.0
7	29.0	29.7	33.0	33.2	29.0	30.2
8	30.0	30.0	33.0	34.0	29.0	31.0
9	28.9	30.5	33.1	34.5	27.4	29.0
10	28.5	30.6	32.5	34.1	27.0	29.1
11	28.0	29.5	32.5	34.5	27.0	29.5
12	28.0	29.8	34.5	35.8	28.0	30.8
13	28.5	30.5	35.0	36.0	32.0	33.0
14	28.1	29.5	33.6	34.5	30.1	31.5
15	28.0	29.3	30.5	32.3	28.0	30.8
16	32.5	32.6	30.5	31.6	30.0	30.6
17	27.6	29.5	34.1	35.0	32.1	33.0
18	28.5	29.5	36.0	36.5	32.0	33.0
19	28.5	29.9	34.5	35.9	28.5	29.4
20	27.0	29.5	33.0	35.5	28.0	29.0
21	-	29.6	34.2	35.1	30.2	-
22	27.0	30.0	34.0	35.5	28.0	30.0
23	28.1	29.5	33.6	35.0	28.6	31.0
24	29.5	30.5	34.5	35.5	33.0	34.0
25	32.5	33.0	30.5	32.0	29.5	31.5
26	30.0	31.0	-	33.0	-	31.0
27	29.3	31.0	32.3	35.0	28.3	31.0
28	33.5	34.5	30.5	31.5	27.5	29.0

TABLE 13

CORRECTED MINIMUM TEMPERATURES IN
DEGREES FAHRENHEIT BY STATIONS

Station	<u>3/11/61</u>	
	1' Level	5' Level
1	28.3	29.0
2	28.5	29.5
3	29.6	30.6
4	28.0	29.4
5	27.5	28.7
6	28.0	28.0
7	30.5	31.2
8	30.5	31.5
9	29.6	31.5
10	28.0	28.6
11	28.0	29.5
12	29.0	31.8
13	31.0	32.0
14	30.1	31.0
15	27.0	28.8
16	28.0	27.6
17	28.6	30.5
18	30.0	31.0
19	30.0	29.9
20	28.5	29.5
21	30.2	-
22	29.5	31.5
23	29.6	30.0
24	29.0	30.5
25	-	27.5
26	-	28.5
27	27.8	29.5
28	27.0	28.0

TABLE 14

CORRECTED TEMPERATURE READINGS IN DEGREES
FAHRENHEIT BY STATIONS FOR THE 9' LEVEL

Station	1/24/59			2/22/59		
	2:30 AM	4:30 AM	6:30 AM	2:00 AM	4:00 AM	6:00 AM
1	36.5	35.0	32.5	37.0	34.5	31.5
2	35.8	34.9	33.0	37.2	34.5	31.9
3	36.2	35.2	32.6	36.9	34.3	32.0
4	36.5	34.9	32.0	37.0	34.0	32.0
5	34.2	34.0	31.5	35.5	32.8	30.0
6	34.9	34.0	32.0	36.0	34.0	32.0
7	35.2	34.9	34.5	37.0	36.2	33.5
8	34.9	36.0	34.5	37.0	36.0	34.5
9	35.8	35.9	33.8	36.8	36.0	33.0
10	35.7	35.5	33.5	36.8	35.5	31.0
11	36.2	35.0	33.0	36.5	34.5	31.0
12	37.0	35.2	33.4	38.5	35.0	34.5
13	36.5	34.5	33.5	37.0	35.0	34.5
14	35.8	34.3	35.0	37.5	34.8	34.0
15	35.0	34.5	33.0	35.8	34.0	32.0
16	34.8	34.3	33.2	35.5	34.0	30.5
17	34.9	34.5	33.9	36.2	34.5	32.0
18	35.2	34.5	35.0	37.0	34.8	33.5
19	36.0	34.6	36.5	36.5	34.5	33.0
20	35.2	35.0	34.0	36.0	34.0	32.2
21	35.0	34.5	33.5	35.8	33.8	32.0
22	35.2	34.2	33.5	35.9	33.8	31.8
23	35.5	36.0	34.5	35.8	34.0	31.0
24	35.0	35.5	34.5	35.6	34.0	32.0
25	34.8	34.5	33.0	35.5	33.5	30.0
26	35.5	34.5	33.5	36.0	33.5	32.0
27	35.7	34.5	33.5	36.0	34.0	32.1
28	34.0	33.2	32.0	35.5	32.6	30.0

TABLE 15

CORRECTED TEMPERATURE READINGS IN DEGREES
FAHRENHEIT BY STATIONS FOR THE 9' LEVEL

Station	3/3/59		2/8/60		2/27/60	
	4:00 AM	6:00 AM	4:00 AM	6:00 AM	3:30 AM	5:30 AM
1	34.2	33.2	34.5	32.5	34.5	32.5
2	34.3	33.3	34.5	32.5	34.8	32.3
3	34.0	33.0	34.5	32.5	34.3	32.0
4	33.5	32.5	34.0	32.0	34.0	32.0
5	33.0	30.5	33.0	30.5	34.0	30.5
6	33.5	32.0	34.0	32.0	34.0	31.0
7	33.0	32.0	35.0	34.2	34.3	32.0
8	33.5	32.0	35.9	33.9	34.5	32.5
9	33.5	32.0	34.5	33.5	34.6	32.5
10	33.5	33.0	34.5	32.9	34.5	32.3
11	34.5	33.5	35.0	32.5	34.3	32.0
12	36.0	34.8	36.0	34.0	34.8	32.5
13	36.0	34.9	35.5	34.0	34.7	32.5
14	33.0	32.5	34.5	34.0	34.5	32.0
15	33.0	32.0	34.0	33.0	34.0	32.0
16	32.5	31.0	33.5	32.5	34.0	32.0
17	33.0	31.0	34.5	33.0	34.0	31.9
18	34.5	33.5	37.1	33.5	34.3	32.0
19	35.0	34.5	34.5	32.5	34.0	32.0
20	33.5	33.2	33.8	32.3	34.0	31.8
21	33.0	32.5	33.5	32.5	33.9	31.5
22	33.0	32.5	33.9	33.0	33.8	31.5
23	33.0	32.5	34.5	33.0	34.0	31.5
24	34.0	32.5	34.0	33.0	34.0	31.0
25	33.0	31.0	33.5	32.5	33.5	31.0
26	33.0	32.0	34.0	32.5	33.9	32.0
27	33.1	32.0	34.0	32.5	33.5	31.8
28	32.0	30.0	33.0	30.7	33.0	31.0

BIOGRAPHICAL SKETCH

Joe Neil Busby was born April 9, 1921, at Hartwell, Georgia. He received all grammar and high school education in Lake County, Florida, and was graduated from Eustis High School in June, 1939. He entered the University of Florida in September, 1939, and pursued work toward a Bachelor of Science degree in agriculture until January, 1942. On January 21, 1942, he was sworn into the United States Army Air Corp and served on active duty in all Combat Theaters during World War II. He was relieved of active duty February 20, 1946, and returned to the University of Florida. He received the degree of Bachelor of Science in Agriculture with Honors in January, 1947, from the University of Florida.

He accepted the position of Assistant County Agent, Manatee County, Bradenton, Florida, with the Agricultural Extension Service upon graduation. He served in this position and as Acting County Agent during the County Agent's leave of absence until November, 1949. In the summer of 1948, he registered for graduate work at the University of Florida. He was transferred to the University as Assistant State Boys' 4-H Club Agent for the Agricultural Extension Service in November, 1949, and remained in this position until June, 1951. Part time graduate work continued during this period.

He was involuntarily recalled to active duty by the U. S. Air Force in June, 1951, and was returned to inactive duty in October,

1952, by request after completing a combat tour in Korea. He accepted a position with the State Plant Board of Florida as Assistant Chief Plant Inspector immediately upon release from active duty and remained in this position until September, 1955. In the meantime, he was readmitted to the Graduate School, University of Florida. In September, 1955, he entered the Graduate School on a full time basis.

In July, 1956, he was appointed Assistant Director of the Agricultural Extension Service, a position he currently holds. He continued studies leading to the degree of Doctor of Philosophy on a part time basis and took leaves of absence to pursue the work full time during two summer school sessions.

This dissertation was prepared under the direction of the chairman of the candidate's supervisory committee and has been approved by all members of that committee. It was submitted to the Dean of the College of Agriculture and to the Graduate Council, and was approved as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

August 12, 1961

Earl Houten
Dean, College of Agriculture

Dean, Graduate School

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